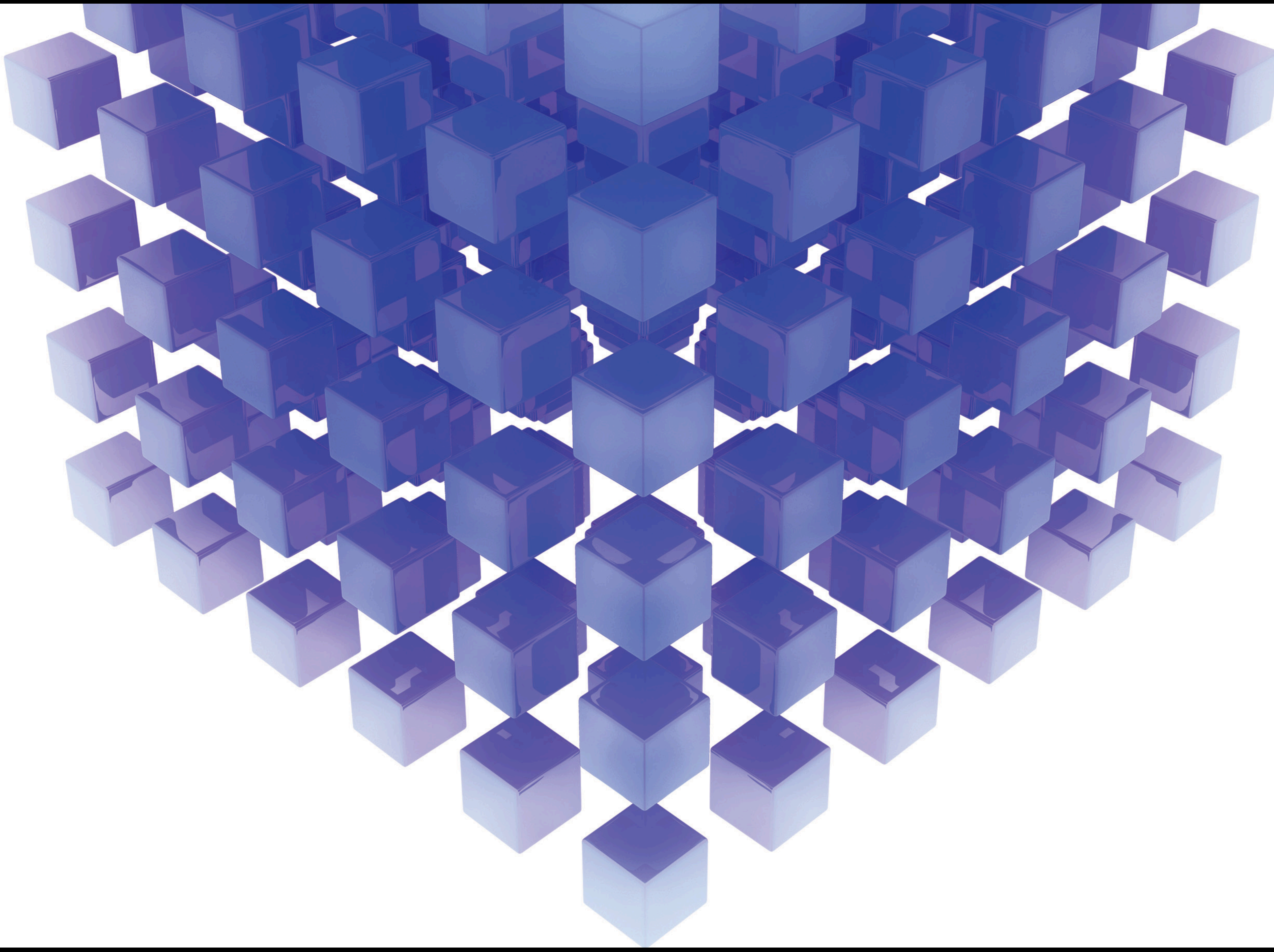
Mathematical Problems in Engineering

Related Theories and Practical Applications of Soft Computing in the Manufacturing Process of Industry 4.0 2021

Lead Guest Editor: Kuei-Hu Chang
Guest Editors: Anthony Shun Fung Chiu and Kim-Hua Tan



Related Theories and Practical Applications of Soft Computing in the Manufacturing Process of Industry 4.0 2021

Mathematical Problems in Engineering

Related Theories and Practical Applications of Soft Computing in the Manufacturing Process of Industry 4.0 2021

Lead Guest Editor: Kuei-Hu Chang
Guest Editors: Anthony Shun Fung Chiu and Kim-Hua Tan

Chief Editor

Editorial Board

Pietro Bia, Italy
Carlo Bianca, France
Vincenzo Bianco, Italy
Vittorio Bianco, Italy
Simone Bianco, Italy
David Bigaud, France
Sardar Muhammad Bilal, Pakistan
Antonio Bilotta, Italy
Dr. Kishore Bingi, India
Sylvio R. Bistafa, Brazil
Bartłomiej Błachowski, Poland
Chiara Boccaletti, Italy
Guido Bolognesi, United Kingdom
Rodolfo Bontempo, Italy
Alberto Borboni, Italy
Marco Bortolini, Italy
Paolo Boscariol, Italy
Daniela Boso, Italy
Guillermo Botella-Juan, Spain
Boulaïd Boulkroune, Belgium
Abdesselem Boulkroune, Algeria
Fabio Bovenga, Italy
Francesco Braghin, Italy
Ricardo Branco, Portugal
Maurizio Brocchini, Italy
Julien Bruchon, France
Matteo Bruggi, Italy
Michele Brun, Italy
Maria Elena Bruni, Italy
Vasilis Burganos, Greece
Maria Angela Butturi, Italy
Dhanamjayulu C, India
Raquel Caballero-Águila, Spain
Guillermo Cabrera-Guerrero, Chile
Filippo Cacace, Italy
Pierfrancesco Cacciola, United Kingdom
Salvatore Caddemi, Italy
zuowei cai, China
Roberto Caldelli, Italy
Alberto Campagnolo, Italy
Eric Campos, Mexico
Salvatore Cannella, Italy
Francesco Cannizzaro, Italy
Maosen Cao, China
Javier Cara, Spain
Raffaele Carli, Italy
Ana Carpio, Spain
Rodrigo Carvajal, Chile
Caterina Casavola, Italy
Sara Casciati, Italy
Federica Caselli, Italy
Carmen Castillo, Spain
Inmaculada T. Castro, Spain
Miguel Castro, Portugal
Giuseppe Catalanotti, United Kingdom
Nicola Caterino, Italy
Alberto Cavallo, Italy
Gabriele Cazzulani, Italy
Luis Cea, Spain
Fatih Vehbi Celebi, Turkey
Song Cen, China
Miguel Cerrolaza, Venezuela
M. Chadli, France
Gregory Chagnon, France
Ludovic Chamoin, France
Xiaoheng Chang, China
Qing Chang, USA
Ching-Ter Chang, Taiwan
Kuei-Lun Chang, Taiwan
Dr. Prasenjit Chatterjee, India
Kacem Chehdi, France
Peter N. Cheimets, USA
Chih-Chiang Chen, Taiwan
Shyi-Ming Chen, Taiwan
Xinkai Chen, Japan
Xizhong Chen, Ireland
Xue-Bo Chen, China
Zhiwen Chen, China
Kebing Chen, China
Mengxin Chen, China
Xiao Chen, China
He Chen, China
Chien-Ming Chen, China
Zeyang Cheng, China
Qiang Cheng, USA
Luca Chiapponi, Italy
Ryoichi Chiba, Japan
Francisco Chicano, Spain
Nicholas Chileshe, Australia
Tirivanhu Chinyoka, South Africa
Adrian Chmielewski, Poland
Seongim Choi, USA
Dr Gautam Choubey, India
Ioannis T. Christou, Greece

Hung-Yuan Chung, Taiwan
Yusheng Ci, China
Simone Cinquemani, Italy
Roberto G. Citarella, Italy
Joaquim Ciurana, Spain
John D. Clayton, USA
Francesco Clementi, Italy
Piero Colajanni, Italy
Giuseppina Colicchio, Italy
Vassilios Constantoudis, Greece
Francesco Conte, Italy
Enrico Conte, Italy
Alessandro Contento, USA
Mario Cools, Belgium
Gino Cortellessa, Italy
Juan Carlos Cortés, Spain
Carlo Cosentino, Italy
Paolo Crippa, Italy
Erik Cuevas, Mexico
Guozeng Cui, China
Maria C. Cunha, Portugal
Mehmet Cunkas, Turkey
Peter Dabnichki, Australia
Luca D'Acierno, Italy
Weizhong Dai, USA
Zhifeng Dai, China
Pei Dai, China
Purushothaman Damodaran, USA
Bhabani S. Dandapat, India
Giuseppe D'Aniello, Italy
Sergey Dashkovskiy, Germany
Adiel T. de Almeida-Filho, Brazil
Fabio De Angelis, Italy
Samuele De Bartolo, Italy
Abílio De Jesus, Portugal
Pietro De Lellis, Italy
Alessandro De Luca, Italy
Stefano de Miranda, Italy
Filippo de Monte, Italy
José António Fonseca de Oliveira Correia, Portugal
Jose Renato de Sousa, Brazil
Michael Defoort, France
Alessandro Della Corte, Italy
Laurent Dewasme, Belgium
Sanku Dey, India
Gianpaolo Di Bona, Italy
Angelo Di Egidio, Italy
Roberta Di Pace, Italy
Francesca Di Puccio, Italy
Ramón I. Diego, Spain
Yannis Dimakopoulos, Greece
Rossana Dimitri, Italy
Hasan Dinçer, Turkey
Alexandre B. Dolgui, France
José M. Domínguez, Spain
Georgios Dounias, Greece
Z. Du, China
Bo Du, China
George S. Dulikravich, USA
Emil Dumic, Croatia
Bogdan Dumitrescu, Romania
Madalina Dumitriu, United Kingdom
Saeed Eftekhar Azam, USA
Said El Kafhali, Morocco
Antonio Elipe, Spain
R. Emre Erkmen, Canada
John Escobar, Colombia
Francisco Periago Esparza, Spain
Gilberto Espinosa-Paredes, Mexico
Leandro F. F. Miguel, Brazil
Andrea L. Facci, Italy
Shahla Faisal, Pakistan
Giovanni Falsone, Italy
Hua Fan, China
Jianguang Fang, Australia
Nicholas Fantuzzi, Italy
Muhammad Shahid Farid, Pakistan
Hamed Faroqi, Iran
Mohammad Fattahi, Iran
Yann Favennec, France
Fiorenzo A. Fazzolari, United Kingdom
Giuseppe Fedele, Italy
Roberto Fedele, Italy
Zhongyang Fei, China
Baowei Feng, China
Mohammad Ferdows, Bangladesh
Arturo J. Fernández, Spain
Jesus M. Fernandez Oro, Spain
Massimiliano Ferraioli, Italy
Massimiliano Ferrara, Italy
Francesco Ferrise, Italy
Constantin Fetecau, Romania
Eric Feulvarch, France

Iztok Fister Jr., Slovenia
Thierry Floquet, France
Eric Florentin, France
Gerardo Flores, Mexico
Antonio Forcina, Italy
Alessandro Formisano, Italy
FRANCESCO FOTI, Italy
Francesco Franco, Italy
Elisa Francomano, Italy
Juan Frausto-Solis, Mexico
Shujun Fu, China
Juan C. G. Prada, Spain
Matteo Gaeta, Italy
Mauro Gaggero, Italy
Zoran Gajic, USA
Jaime Gallardo-Alvarado, Mexico
Mosè Gallo, Italy
Akemi Gálvez, Spain
Rita Gamberini, Italy
Maria L. Gandarias, Spain
Hao Gao, Hong Kong
Xingbao Gao, China
Zhong-Ke Gao, China
Yan Gao, China
Shangce Gao, Japan
Zhiwei Gao, United Kingdom
Giovanni Garcea, Italy
José García, Chile
Luis Rodolfo Garcia Carrillo, USA
Jose M. Garcia-Aznar, Spain
Harish Garg, India
Akhil Garg, China
Alessandro Gasparetto, Italy
Gianluca Gatti, Italy
Oleg V. Gendelman, Israel
Stylianos Georgantzinos, Greece
Fotios Georgiades, India
Parviz Ghadimi, Iran
Ştefan Cristian Gherghina, Romania
Ganesh Ghorai, India
Georgios I. Giannopoulos, Greece
Agathoklis Giaralis, United Kingdom
Pablo Gil, Spain
Anna M. Gil-Lafuente, Spain
Ivan Giorgio, Italy
Gaetano Giunta, Luxembourg
Alessio Gizzi, Italy
Alireza Goli, Iran
Jefferson L.M.A. Gomes, United Kingdom
HECTOR GOMEZ, Chile
José Francisco Gómez Aguilar, Mexico
Emilio Gómez-Déniz, Spain
Antonio M. Gonçalves de Lima, Brazil
Qunxi Gong, China
Chris Goodrich, USA
Rama S. R. Gorla, USA
Veena Goswami, India
Xunjie Gou, Spain
Jakub Grabski, Poland
Antoine Grall, France
George A. Gravvanis, Greece
Fabrizio Greco, Italy
David Greiner, Spain
Jason Gu, Canada
Federico Guarracino, Italy
Michele Guida, Italy
Muhammet Gul, Turkey
NALLAPPAN GUNASEKARAN, Japan
Dong-Sheng Guo, China
Hu Guo, China
Zhaoxia Guo, China
Jian-Ping Guo, China
Yusuf Gurefe, Turkey
Quang Phuc Ha, Australia
Li Haitao, China
Petr Hájek, Czech Republic
Mohamed Hamdy, Egypt
Muhammad Hamid, United Kingdom
Shigeyuki Hamori, Japan
Renke Han, United Kingdom
Weimin Han, USA
Zhen-Lai Han, China
Xingsi Han, China
Thomas Hanne, Switzerland
Xinan Hao, China
Mohammad A. Hariri-Ardebili, USA
Khalid Hattaf, Morocco
Defeng He, China
Xiao-Qiao He, China
Fu-Qiang He, China
Yanchao He, China
Yu-Ling He, China
salim HEDDAM, Algeria
Ramdane Hedjar, Saudi Arabia

Jude Hemanth, India
Reza Hemmati, Iran
Nicolae Herisanu, Romania
Alfredo G. Hernández-Diaz, Spain
M.I. Herreros, Spain
Eckhard Hitzer, Japan
Paul Honeine, France
Jaromir Horacek, Czech Republic
S. Hassan Hosseinnia, The Netherlands
Yingkun Hou, China
Lei Hou, China
Xiaorong Hou, China
Jie Hu, China
Yunfeng Hu, China
Yu-Chen Hu, Taiwan
Can Huang, China
Gordon Huang, Canada
Linsheng Huo, China
Sajid Hussain, Canada
ABID HUSSANAN, China
Asier Ibeas, Spain
Wubshet Ibrahim, Ethiopia
Orest V. Iftime, The Netherlands
Przemyslaw Ignaciuk, Poland
Muhammad Imran, Pakistan
Mukherjee IN, India
Giacomo Innocenti, Italy
Emilio Insfran Pelozo, Spain
Azeem Irshad, Pakistan
Alessio Ishizaka, France
Nazrul Islam, USA
Benoit Iung, France
Benjamin Ivorra, Spain
Breno Jacob, Brazil
Tushar Jain, India
Amin Jajarmi, Iran
Payman Jalali, Finland
Mahdi Jalili, Australia
Prashant Kumar Jamwal, Kazakhstan
Chiranjibe Jana, India
Łukasz Jankowski, Poland
Fahd Jarad, Turkey
Samuel N. Jator, USA
Juan C. Jauregui-Correa, Mexico
Kandasamy Jayakrishna, India
Reza Jazar, Australia
Khalide Jbilou, France
Isabel S. Jesus, Portugal
Chao Ji, China
Linni Jian, China
Bin Jiang, China
Qing-Chao Jiang, China., China
Peng-fei Jiao, China
Ricardo Fabricio Escobar Jiménez, Mexico
Emilio Jiménez Macías, Spain
Zhuo Jin, Australia
Xiaoliang Jin, Canada
Maolin Jin, Republic of Korea
Dylan F. Jones, United Kingdom
Ramash Kumar K, India
Viacheslav Kalashnikov, Mexico
Mathiyalagan Kalidass, India
BHABEN KALITA, USA
Tamas Kalmar-Nagy, Hungary
Rajesh Kaluri, India
Zhao Kang, China
Ramani Kannan, Malaysia
Tomasz Kapitaniak, Poland
Julius Kaplunov, United Kingdom
Konstantinos Karamanos, Belgium
J. Kavikumar, Malaysia
Michal Kawulok, Poland
Irfan Kaymaz, Turkey
Vahid Kayvanfar, Iran
Krzysztof Kecik, Poland
Mohamed Khader, Egypt
Chaudry M. Khalique, South Africa
Umar Khan, Pakistan
Shahid Khan, Pakistan
Mukhtaj Khan, Pakistan
Abdul Qadeer Khan, Pakistan
Mostafa M. A. Khater, Egypt
MOHAMMAD REZA KHEDMATI, Iran
Nam-Il Kim, Republic of Korea
Kwangki Kim, Republic of Korea
Philipp V. Kiryukhantsev-Korneev, Russia
P.V.V Kishore, India
Jan Koci, Czech Republic
Ioannis Kostavelis, Greece
Sotiris B. Kotsiantis, Greece
Frederic Kratz, France
Vamsi Krishna, India
Kamalanand Krishnamurthy, India
Petr Krysl, USA

Francisco J. Martos, Spain
Elio Masciari, Italy
Franck Massa, France
Paolo Massioni, France
Alessandro Mauro, Italy
Jonathan Mayo-Maldonado, Mexico
Fabio Mazza, Italy
Pier Luigi Mazzeo, Italy
Laura Mazzola, Italy
Driss Mehdi, France
Dr. Zahid Mehmood, Pakistan
YUE MEI, China
Roderick Melnik, Canada
Debiao Meng, China
Xiangyu Meng, USA
Jose Merodio, Spain
Alessio Merola, Italy
Mahmoud Mesbah, Iran
Luciano Mescia, Italy
Laurent Mevel, France
Constantine Michailides, Cyprus
Mariusz Michta, Poland
Prankul Middha, Norway
Aki Mikkola, Finland
Giovanni Minafò, Italy
Hiroyuki Mino, Japan
Dimitrios Mitsotakis, New Zealand
saleh mobayen, Taiwan, R.O.C., Iran
Nikunja Mohan Modak, India
Ardashir Mohammadzadeh, Iran
Sara Montagna, Italy
Roberto Montanini, Italy
Francisco J. Montáns, Spain
Francesco Montefusco, Italy
Gisele Mophou, France
Rafael Morales, Spain
Marco Morandini, Italy
Javier Moreno-Valenzuela, Mexico
Simone Morganti, Italy
Caroline Mota, Brazil
Aziz Moukrim, France
Shen Mouquan, China
Dimitris Mourtzis, Greece
Emiliano Mucchi, Italy
Taseer Muhammad, Saudi Arabia
Ghulam Muhiuddin, Saudi Arabia
Josefa Mula, Spain
Jose J. Muñoz, Spain
Giuseppe Muscolino, Italy
Dino Musmarra, Italy
Marco Mussetta, Italy
Ghulam Mustafa, Pakistan
Hariharan Muthusamy, India
Hakim Naceur, France
Alessandro Naddeo, Italy
Benedek Nagy, Turkey
Omar Naifar, Tunisia
Mariko Nakano-Miyatake, Mexico
Raj Nandkeolyar, India
Keivan Navaie, United Kingdom
Soumya Nayak, India
Adrian Neagu, USA
Erivelton Geraldo Nepomuceno, Brazil
Luís C. Neves, United Kingdom
AMA Neves, Portugal
Ha Quang Thinh Ngo, Vietnam
Dong Ngoduy, New Zealand
Nhon Nguyen-Thanh, Singapore
Majid Niazkar, Italy
Papakostas Nikolaos, Ireland
Jelena Nikolic, Serbia
Mehrbakhsh Nilashi, Malaysia
Tatsushi Nishi, Japan
Shanzhou Niu, China
Xesús Nogueira, Spain
Ben T. Nohara, Japan
Mohammed Nouari, France
Mustapha Nourelfath, Canada
Kazem Nouri, Iran
Ciro Núñez-Gutiérrez, Mexico
Wlodzimierz Ogryczak, Poland
Roger Ohayon, France
Krzysztof Okarma, Poland
Mitsuhiro Okayasu, Japan
Murat Olgun, Turkey
Diego Oliva, Mexico
Alberto Olivares, Spain
Enrique Onieva, Spain
Calogero Orlando, Italy
Sergio Ortobelli, Italy
Naohisa Otsuka, Japan
Sid Ahmed Ould Ahmed Mahmoud, Saudi Arabia
Taoreed Owolabi, Nigeria

Abdolrahman Razani, Iran
Alessandro Reali, Italy
Jose A. Reinoso, Spain
Oscar Reinoso, Spain
X. W. Ren, China
Haijun Ren, China
Carlo Renno, Italy
Fabrizio Renno, Italy
Shahram Rezapour, Iran
Ricardo Riaza, Spain
Francesco Riganti-Fulginei, Italy
Gerasimos Rigatos, Greece
Francesco Ripamonti, Italy
Marcelo Raúl Risk, Argentina
Jorge Rivera, Mexico
Eugenio Roanes-Lozano, Spain
Bruno G. M. Robert, France
Ana Maria A. C. Rocha, Portugal
Luigi Rodino, Italy
Francisco Rodríguez, Spain
Rosana Rodríguez López, Spain
Alessandra Romolo, Italy
Abdolreza Roshani, Italy
Francisco Rossomando, Argentina
Sudipta Roy, India
Jose de Jesus Rubio, Mexico
Weiguo Rui, China
Rubén Ruiz, Spain
Ivan D. Rukhlenko, Australia
Dr. Eswaramoorthi S., India
Chaman Lal Sabharwal, USA
Kishin Sadarangani, Spain
Andrés Sáez, Spain
Bekir Sahin, Turkey
Laxminarayan Sahoo, India
Michael Sakellariou, Greece
John S. Sakellariou, Greece
Salvatore Salamone, USA
Jose Vicente Salcedo, Spain
Alejandro Salcido, Mexico
Alejandro Salcido, Mexico
Salman saleem, Saudi Arabia
Ahmed Salem, Saudi Arabia
Nunzio Salerno, Italy
Rohit Salgotra, India
Miguel A. Salido, Spain
Zabidin Salleh, Malaysia
Roque J. Saltarén, Spain
Alessandro Salvini, Italy
Abdus Samad, India
Sovan Samanta, India
Nikolaos Samaras, Greece
Sylwester Samborski, Poland
pijush samui, India
Ramon Sancibrian, Spain
Giuseppe Sanfilippo, Italy
Omar-Jacobo Santos, Mexico
J Santos-Reyes, Mexico
José A. Sanz-Herrera, Spain
Evangelos J. Sapountzakis, Greece
Musavarah Sarwar, Pakistan
Marcelo A. Savi, Brazil
Andrey V. Savkin, Australia
Tadeusz Sawik, Poland
Roberta Sburlati, Italy
Gustavo Scaglia, Argentina
Thomas Schuster, Germany
Hamid M. Sedighi, Iran
Mijanur Rahaman Seikh, India
Tapan Senapati, China
Lotfi Senhadji, France
Junwon Seo, USA
Michele Serpilli, Italy
Joan Serra-Sagrista, Spain
Silvestar Šesnić, Croatia
Erhan Set, Turkey
Gerardo Severino, Italy
Ruben Sevilla, United Kingdom
Stefano Sfarra, Italy
Mohamed Shaat, United Arab Emirates
Mostafa S. Shadloo, France
Dr. Zahir Shah, Pakistan
Dr. Ismail Shah, Pakistan
Kamal Shah, Pakistan
Leonid Shaikhet, Israel
Vimal Shanmuganathan, India
Xingling Shao, China
Prayas Sharma, India
Xin Pu Shen, China
Bo Shen, Germany
hang shen, China
Hao Shen, China
Dimitri O. Shepelsky, Ukraine
Weichao SHI, United Kingdom

Jian Shi, China
Suzanne M. Shontz, USA
Babak Shotorban, USA
Zhan Shu, Canada
Angelo Sifaleras, Greece
Luca Silvestri, Italy
Nuno Simões, Portugal
Mehakpreet Singh, Ireland
Harendra Singh, India
Rajiv Singh, India
Thanin Sitthiwirattham, Thailand
Seralathan Sivamani, India
S. Sivasankaran, Malaysia
Christos H. Skiadas, Greece
Konstantina Skouri, Greece
Neale R. Smith, Mexico
Bogdan Smolka, Poland
Delfim Soares Jr., Brazil
Alba Sofi, Italy
Francesco Soldovieri, Italy
Raffaele Solimene, Italy
Yang Song, Norway
Bosheng Song, China
Jussi Sopanen, Finland
Marco Spadini, Italy
Paolo Spagnolo, Italy
Bernardo Spagnolo, Italy
Ruben Specogna, Italy
Vasilios Spitas, Greece
Sri Sridharan, USA
Ivanka Stamova, USA
Rafał Stanisławski, Poland
Miladin Stefanović, Serbia
Florin Stoican, Romania
ALBERT ALEXANDER STONIER, India
Salvatore Strano, Italy
Yakov Strelniker, Israel
Kumarasamy Sudhakar, Malaysia
Zong-Yao Sun, China
Kangkang Sun, China
Qiuqin Sun, China
Shuaishuai Sun, Australia
Xiaodong Sun, China
Qiuye Sun, China
Suroso Suroso, Indonesia
Sergey A. Suslov, Australia
Nasser Hassen Sweilam, Egypt
Andrzej Swierniak, Poland
M Syed Ali, India
Andras Szekrenyes, Hungary
Kumar K. Tamma, USA
Yong (Aaron) Tan, United Kingdom
Marco Antonio Taneco-Hernández, Mexico
Hafez Tari, USA
Alessandro Tasora, Italy
Sergio Teggi, Italy
Adriana del Carmen Téllez-Anguiano, Mexico
Ana C. Teodoro, Portugal
Efstathios E. Theotokoglou, Greece
Jing-Feng Tian, China
Alexander Timokha, Norway
Stefania Tomasiello, Italy
Gisella Tomasini, Italy
Isabella Torcicollo, Italy
Francesco Tornabene, Italy
Javier Martinez Torres, Spain
Mariano Torrisi, Italy
Thang nguyen Trung, Vietnam
Sang-Bing Tsai, China
George Tsiatas, Greece
Antonios Tsourdos, United Kingdom
Le Anh Tuan, Vietnam
Federica Tubino, Italy
Nerio Tullini, Italy
Emilio Turco, Italy
Ilhan Tuzcu, USA
Efstratios Tzirtzilakis, Greece
Filippo Ubertini, Italy
Marjan Uddin, Pakistan
Mohammad Uddin, Australia
Serdar Ulubeyli, Turkey
Mati ur Rahman, Pakistan
FRANCISCO UREÑA, Spain
Panayiotis Vafeas, Greece
Giuseppe Vairo, Italy
Jesus Valdez-Resendiz, Mexico
Eusebio Valero, Spain
Stefano Valvano, Italy
Marcello Vasta, Italy
Carlos-Renato Vázquez, Mexico
Miguel E. Vázquez-Méndez, Spain
Martin Velasco Villa, Mexico
Kalyana C. Veluvolu, Republic of Korea

Franck J. Vernerey, USA
Georgios Veronis, USA
Vincenzo Vespri, Italy
Renato Vidoni, Italy
Venkatesh Vijayaraghavan, Australia
Anna Vila, Spain
Francisco R. Villatoro, Spain
Francesca Vipiana, Italy
Stanislav Vítek, Czech Republic
Jan Vorel, Czech Republic
Michael Vynnycky, Sweden
Mohammad W. Alomari, Jordan
Fu-Kwun Wang, Taiwan
C. H. Wang, Taiwan
Yung-Chung Wang, Taiwan
Hao Wang, USA
Zhenbo Wang, USA
Zenghui Wang, South Africa
Yongqi Wang, Germany
Weiwei Wang, China
Dagang Wang, China
Yong Wang, China
Bingchang Wang, China
Ji Wang, China
Lei Wang, China
Hui Wang, China
Huaiyu Wang, China
qiang wang, China
Kang-Jia Wang, China
J.G. Wang, China
Guoqiang Wang, China
Zhibo Wang, China
Shuo Wang, China
Qingling Wang, China
Xinyu Wang, China
Roman Wan-Wendner, Austria
Fangqing Wen, China
P.H. Wen, United Kingdom
Waldemar T. Wójcik, Poland
Wai Lok Woo, United Kingdom
Qiuhong Wu, China
Xianyi Wu, China
Chi Wu, Australia
Zhizheng Wu, China
Yuqiang Wu, China
Zhibin Wu, China
Changzhi Wu, China
Michalis Xenos, Greece
hao xiao, China
Xiao Ping Xie, China
Xue-Jun Xie, China
Hang Xu, China
Lei Xu, China
Qingzheng Xu, China
Zeshui Xu, China
Lingwei Xu, China
Qilong Xue, China
Yi Xue, China
Binghan Xue, China
Joseph J. Yame, France
Zhiguo Yan, China
Chuanliang Yan, China
Xinggang Yan, United Kingdom
Ray-Yeng Yang, Taiwan
Mijia Yang, USA
Jixiang Yang, China
Hongtai Yang, China
Zaoli Yang, China
Bo Yang, China
Weilin Yang, China
Zhihong Yao, China
Min Ye, China
Jun Ye, China
Luis J. Yebra, Spain
Peng-Yeng Yin, Taiwan
Muhammad Haroon Yousaf, Pakistan
Yuan Yuan, United Kingdom
Qin Yuming, China
Abdullahi Yusuf, Nigeria
Akbar Zada, Pakistan
Elena Zaitseva, Slovakia
Arkadiusz Zak, Poland
Muhammad Zakarya, Pakistan
Daniel Zaldivar, Mexico
Ernesto Zambrano-Serrano, Mexico
Francesco Zammori, Italy
Rafal Zdunek, Poland
Ahmad Zeeshan, Pakistan
Ibrahim Zeid, USA
Bo Zeng, China
Nianyin Zeng, China
Junyong Zhai, China
Jian Zhang, China
Yong Zhang, China

Qian Zhang, China
Tongqian Zhang, China
Xiaofei Zhang, China
Lingfan Zhang, China
Wenyu Zhang, China
Kai Zhang, China
Hao Zhang, China
Xuping Zhang, Denmark
Yinyan Zhang, China
Tianwei Zhang, China
Xianming Zhang, Australia
Haopeng Zhang, USA
Mingjie Zhang, Norway
Yifan Zhao, United Kingdom
Yongmin Zhong, Australia
Zebo Zhou, China
Zhe Zhou, China
Jian G. Zhou, United Kingdom
Debao Zhou, USA
Quanxin Zhu, China
Wu-Le Zhu, China
Gaetano Zizzo, Italy
Zhixiang Zou, China
Mingcheng Zuo, China

Contents

Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 9802892, 2 pages
https://doi.org/10.1155/2022/9802892

Editorial

Related Theories and Practical Applications of Soft Computing in the Manufacturing Process of Industry 4.0 2021

Kuei-Hu Chang,[1] **Anthony Shun Fung Chiu**,[2] **and Kim-Hua Tan**[3]

[1]*Department of Management Sciences, R.O.C. Military Academy, Kaohsiung 830, Taiwan*
[2]*Department of Industrial & Systems Engineering, De La Salle University, Manila, Philippines*
[3]*Division of Operations Management and Information Systems, University of Nottingham, Nottingham, UK*

Correspondence should be addressed to Kuei-Hu Chang; evenken2002@gmail.com

Received 30 June 2022; Accepted 30 June 2022; Published 11 August 2022

Soft computing includes machine learning, computer science, and computing technologies in certain engineering disciplines. Soft computing enables research, simulation, and analysis of complex problems and phenomena. Moreover, related developmental theories can be applied and used to solve problems that occurred in the manufacturing process of Industry 4.0.

Industry 4.0 is also known as industrial internet, smart factory, or advanced manufacturing. With the assistance of new technologies such as the Internet of Things (IoT) and the wide applications of mobile technologies, organizations generate large amounts of data in different formats at a faster rate than before. In addition, data content, process, analytical model, and management of big data transformation have also developed huge challenges and opportunities. Hence, advanced soft computing methods and decision-making techniques can be used to extract useful information and obtain effective manufacturing intelligence. They combine the algorithms with related decision-making techniques from the big data to make equipment automation. In addition, they are able to detect potential failures in the early stage under certain circumstances, diagnose defects, control advanced equipment/process, decrease cycle time and costs, and increase productive rate. The aim and scope can cover wide ranges of fields such as artificial intelligence (AI), robotics, Internet of Things (IoT), autonomous vehicle, 3D printing, nanotechnology, materials science, and energy storage.

The aim of this special issue is to bring together original research and review articles regarding the latest developments, problems, and challenges of the applications of soft computing in the manufacturing process of Industry 4.0. Many papers were submitted to this special issue; however, through a strict peer review process, only 14 articles were accepted in this special issue. We summarize these 14 papers as follows.

In the research article "An Adaptive Location-Based Tracking Algorithm Using Wireless Sensor Network for Smart Factory Environment," the authors Chiu et al. combined the Kalman filter and the adaptive network based on the fuzzy inference system to present a new adaptive location base service algorithm for the smart factory environment. Chiu et al. applied Kalman filter characteristics to eliminate noise in the signal transmission process in order to improve the stability and accuracy of localization. Moreover, the authors used the adaptive network based on the fuzzy inference system to obtain the environment parameter of the target.

In the research article "Evaluate the Consumer Acceptance of AIoT-Based Unmanned Convenience Stores Based on Perceived Risks and Technological Acceptance Models," Wang et al. combined the technology acceptance model and the perceived risks of customers and used multivariate analysis of variance to evaluate the consumer acceptance of unmanned convenience stores. Their method were easy to use, in addition, the results showed that behavioral intentions and positive attitude of male consumers are all significantly higher than female consumers for the unmanned convenience stores based on the artificial intelligence Internet of Things. Conversely, male consumers had a lower perceived risk than female consumers.

In the research article "Establishing an AI Model on Data Sensing and Prediction for Smart Home Environment Control Based on LabVIEW," the authors Yao et al. used laboratory virtual instrument engineering workbench as the main architecture for smart home systems to achieve the intelligent control at home environment. Furthermore, they utilized Python to construct the artificial neural network intelligence model to collect information and forecast data.

In the research article "A Deep Learning Model of Dual-Stage License Plate Recognition Applicable to the Data Processing Industry," Tung et al. presented the dual-stage license plate recognition model to confirm the license plate detection. They combined the convolutional recurrent neural network and the connectionist temporal classification to conduct training loss function for automatic recognition of the license plate.

In the research article "A Novel Contractor Selection Technique Using the Extended PROMETHEE II Method," the author Chang combined the soft set concept and the PROMETHEE II method to propose the novel contractor selection technique. For incomplete information, the author used the weighted arithmetic averaging method to fill in the data and used the PROMETHEE II method to deal with the experts' subjective preferences and relative importance of criteria.

In the research article "In a Stressful Social Environment, Can Using Sports Apps Relieve the Physical and Mental Stress of the Elderly? From the Perspective of Industry 4.0," Huan et al. explored whether using sport apps can relieve elderlies' physical and mental stress when facing COVID-19 pandemic. Their research confirmed that the lower the intensity of leisure exercise, the more the negative emotions they may produce from the elderlies. In the research article "Effects of Output Quality and Result Demonstrability on the Perceived Usefulness of GPS Sports Watches from the Perspective of Industry 4.0," Yuan et al. used the concept of Industry 4.0 to explore the impact of GPS sports watches on the perceived usefulness of users. In the research article "Uplink Spectrum Overlay Coverage Enhancement Algorithm in 5G Network," Jiang and Ding proposed the 5G network-based uplink coverage enhancement algorithm to handle the uplink and downlink coverage issues of 5G network.

Pannakkong et al. used the artificial neural network, support vector machine, and deep belief network to perform the hyperparameter tuning in machine learning algorithms. Chen et al. combined the decision-making and trial evaluation laboratory (DEMATEL) and the DEMATEL analytic network process (DANP) method to explore the business model in affiliated restaurants. Tripathi et al. proposed a new smart production management system to handle the complex shop-floor problems in Industry 4.0. Chang integrated the hesitant fuzzy linguistic term sets and minimal variance ordered weighted average (MVOWA) to handle the supplier selection issues of hesitant information. Guo et al. proposed the time-delayed feedback control algorithm strategy for the vehicle semiactive suspension system. Tripathi et al. proposed the data-driven decision-making system to regulate the shop floor management of uncertain production conditions in Industry 4.0.

Although the papers published in this special issue is very limited for the field of soft computing in the manufacturing process of Industry 4.0, we still believe that the 14 papers of these special issues will provide positive contributions in the manufacturing process of Industry 4.0. We are looking forward to provide follow-up researchers with more ideas and research directions in related research fields.

Data Availability

All data were obtained from the published studies.

Conflicts of Interest

The Guest Editors declare that they have no conflicts of interest regarding the publication of this special issue.

Acknowledgments

We would like to express our gratitude to all contributors who contributed their original papers that are published in this special issue. We also thank all reviewers for reviewing articles and providing constructive review comments and suggestions. In addition, we would like to express our gratitude to the Editorial Board of *Mathematical Problems in Engineering* journal and Hindawi for assisting and completing the publication of this special issue.

Kuei-Hu Chang
Anthony Shun Fung Chiu
Kim-Hua Tan

Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 3012215, 20 pages
https://doi.org/10.1155/2022/3012215

Research Article

Development of a Data-Driven Decision-Making System Using Lean and Smart Manufacturing Concept in Industry 4.0: A Case Study

Varun Tripathi,[1] Somnath Chattopadhyaya,[2] A. K. Mukhopadhyay,[3] Suvandan Saraswat,[4] Shubham Sharma ,[5,6] Changhe Li,[7] and S. Rajkumar [8]

[1]*Department of Mechanical Engineering, Accurate Institute of Management & Technology, Greater Noida, UP, India*
[2]*Indian Institute of Technology (ISM), Dhanbad, India*
[3]*Department of Mining Machinery Engineering, Indian Institute of Technology (ISM), Dhanbad, India*
[4]*Department of Mechanical Engineering, JSS Academy of Technical Education, Noida, India*
[5]*Department of Mechanical Engineering, IK Gujral Punjab Technical University, Main Campus, Kapurthala 144603, Punjab, India*
[6]*Mechanical Engineering Department, University Center for Research & Development, Chandigarh University, Mohali 140413, Punjab, India*
[7]*School of Mechanical and Automotive Engineering, Qingdao University of Technology, Qingdao 266520, China*
[8]*Department of Mechanical Engineering, Faculty of Manufacturing, Institute of Technology, Hawassa University, Awasa, Ethiopia*

Correspondence should be addressed to Shubham Sharma; shubham543sharma@gmail.com and S. Rajkumar; rajkumar@hu.edu.et

Received 23 October 2021; Revised 25 December 2021; Accepted 28 March 2022; Published 12 May 2022

Academic Editor: Kuei-Hu Chang

Nowadays, industries are emphasizing the implementation of a smart shop floor management method because of different types of problems faced in controlling the production activities in Industry 4.0. Several shop floor management methods are currently implemented in the present Industry 4.0 scenario, including lean manufacturing, logistics, Internet of things, smart manufacturing, cyber-physical system, and artificial intelligence. The present research work is focused on the development and Taguchi validation methodology of a data-driven decision-making system using L_9 orthogonal array for smart shop floor management based on the relationship between production sustainability and constraints. The proposed system has been validated by a comprehensive investigation of a case of mining machinery manufacturing unit. The result of the investigation revealed that productivity has been enhanced by effective controlling of production activities on the shop floor. Taguchi L_9 orthogonal array method of design of experiments is implemented to enhance flexibility for shop floor control and meanwhile minimize the production time due to inefficient operating conditions on the shop floor. Taguchi method was implemented for critical conditions affecting production lead time and resource utilization. The authors have detailed discussion on developing present novel hybrid integration of lean and smart manufacturing approaches to enhance operational excellence in production activities and other complicated manufacturing environment on the shop floor within available resources. The present finding demonstrates that the adopted digital technologies under smart manufacturing with lean manufacturing are found to be cost-effective approach under different environmental conditions. The proposed system has significantly improved the efficiency of production management and operational performance by using smart systems and has proved effective in improving the financial position by making a safer shop floor management approach. In this article, a robust problem-solving system is provided. The present work aims to introduce revolutionary methods for Industry 4.0 that would result in productivity enhancement and beneficial impact on industry persons by improving the smart shop floor management. The study also provides valuable perspective and sustainable guidelines to facilitate industry individuals to implement lean and smart manufacturing for productivity enhancement in the production environment of Industry 4.0.

1. Introduction

Nowadays, the primary demand of Industry 4.0 is to control production within available resources. For this, advanced shop floor management methods are used to control the production in the present scenario [1]. The main objective of shop floor management is to maximize productivity within limited constraints [2, 3]. In Industry 4.0, smart manufacturing, logistics, Internet of things, lean manufacturing, cyber-physical system, and artificial intelligence are used for operation management on the shop floor [4]. These methods are based on different principles, but they have the same objective—how to optimize the production processes efficiently. These methods are used to control the operational excellence of production processes in different working conditions. Figures 1(a) and 1(b) describe methods and objectives of advanced shop floor management in Industry 4.0.

The shop floor management concept was originated from Toyota Production System after the crisis in production management in terms of higher production time, higher cost, poor quality, insecure environment, and higher resource utilization [5]. The concept is used to eliminate sources of non-value-added activity (waste) and to plan an efficient work plan for productivity enhancement [6, 7]. With the passage of time, the production system changes and the need for advanced methods started increasing. To accomplish this, traditional methods are changed and modified. The developed methods are implemented to enhance production in Industry 4.0 [8]. The main aim of developed methods is to eliminate waste found in different production conditions on the shop floor [9]. In previous research, several strategies were used to identify waste found in production conditions and to investigate the real shop floor condition and constraints of the relevant production management system. Figure 2 illustrates the strategies implemented in previous research works to identify wastes.

Previous research shows that production performance depends on several factors like production planning, activities, intelligent system availability, working environment, automation adaptability, sensors, and availability of resources [10]. However, the improvements in productivity from the discussed methodology were poorer than the improvements achieved from a systematic strategy using the advanced shop floor management concept. The advanced shop floor management approach is introduced as a production reformer, and it helps to increase productivity within limited constraints [11]. Constraints are the limits of the management system, and they are found in mainly three forms in industries. Figure 3 describes the constraints faced in the production management system on the shop floor in Industry 4.0.

The shop floor management approaches are used to eliminate waste found in production processes in the industry [12]. Previous researchers have been used in various methods to enhance operational performance in production processes by eliminating waste. Table 1 shows what has been done so far in the past in terms of the methodology used in previous research works.

Researchers have been appreciated smart manufacturing, lean manufacturing, and the Internet of things to production enhancement in Industry 4.0. Other shop floor management methods like Kaizen and lean six sigma have been used by some researchers. Because these methods can be applied only in specific production situations with many limitations. These methods use traditional strategies which are not beneficial in Industry 4.0. To increase the effectiveness of all these methods, they were integrated with advanced shop floor management methods and called the hybrid approach. The hybrid approach has been implemented in previous research, which mainly includes lean smart manufacturing, lean Kaizen, and smart Kaizen. The authors of the present research are studying the methodologies developed in previous research works to clarify the message. The research gap and conclusion identified by previous research work are as follows:

(i) All the studies that have developed the system for shop floor management applications in the production environment concluded that improving the work plan can reduce production parameters but concluded that this is not a generalized strategy that can apply in all types of the Industry 4.0 production environment.

(ii) There is no clarity in previous research on how to enhance production in Industry 4.0 by identification of waste. Therefore, the shortcomings of the previous studies reported in the literature were mainly the lack of control systems implemented for smart shop floor mapping in factories.

However, only a few studies in the open literature studied the methodology development to control shop floor management for enhancement in productivity in Industry 4.0. Nevertheless, several methodologies have been developed to improve the production process using shop floor management methods. This study analyses advanced shop floor management methods implementation in Industry 4.0 by a developed methodology. The following questions are raised as part of the research work objective:

(i) How to demonstrate the problem-solving key of shop floor management in Industry 4.0 through an efficient method using a methodology for reducing nonproductive activities (waste) influencing productivity level.

(ii) How to identify wastes in the production environment by applying the proposed methodology. Here, the production environment refers to higher productivity levels within limited constraints.

The present research work is focused on the development of a novel methodology using lean and smart manufacturing for control of uncertain production management system based on the relationship between shop floor management and resource availability.

2. Research Methodology

The development of a methodology is a systematic strategy to implement shop floor management methods that the regulation of production can be possible. In previous studies,

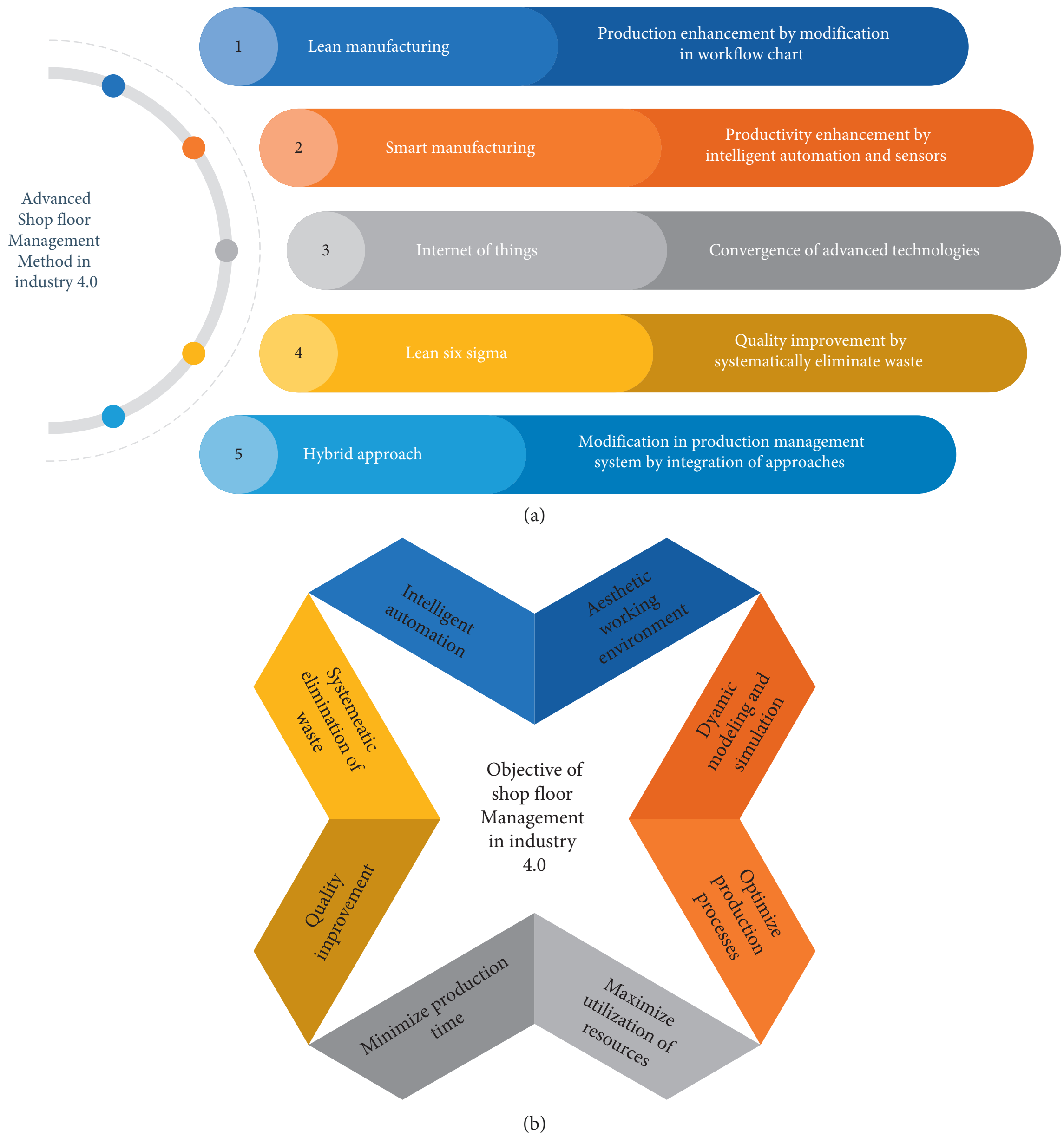


Figure 1: (a) Illustration of shop floor management methods in industry 4.0. (b) Illustration of objective of advanced shop floor management in industry 4.0.

researchers developed a system to improve the effectiveness of shop floor management methods for enhancement in productivity. In the proposed methodology, emphasis was laid on improving the control of resource utilization according to the shop floor management system in Industry 4.0. The following features distinguish the proposed methodology and prove essential for implementing the shop floor management method:

(i) The proposed system helps in identifying the reason for waste and source of waste and investigates the impact of the shop floor management method on the production environment in Industry 4.0.

(ii) The proposed data-driven decision-making system provides a systemic illustration of the shop floor, and it helps the management system to control production process and activities in smart factory.

(iii) The developed system enhances production within limited constraints, through advanced shop floor management methods including smart manufacturing, Internet of things, and cyber-physical system.

(iv) The proposed system can be implemented in Industry 4.0 and obtain industrial sustainability using smart sensor-based system.

The data-driven decision-making system has been developed to improve and regulate the production processes within limited constraints. Figure 4 describes the proposed system for shop floor management in Industry 4.0.

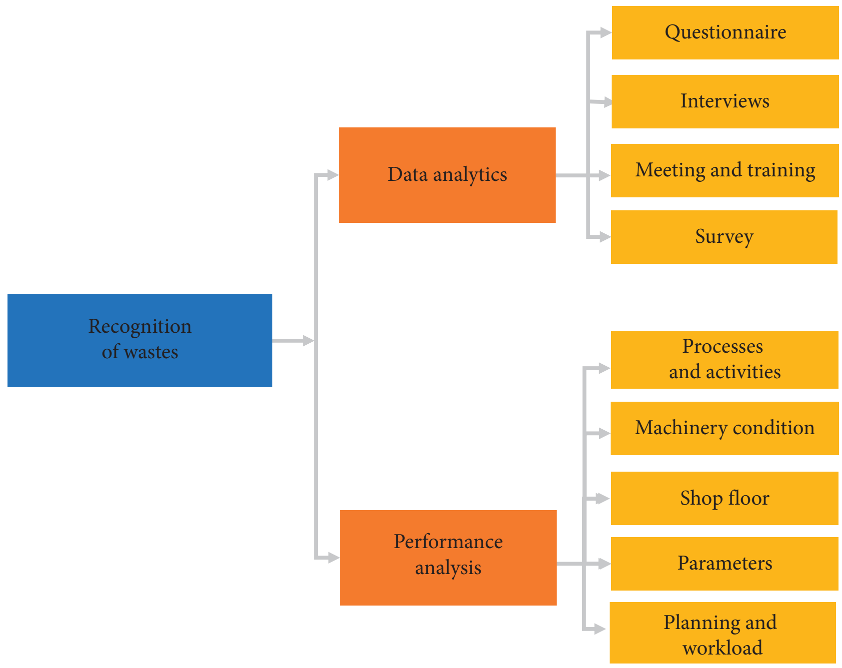


Figure 2: Strategies implemented in previous works in recognition of wastes.

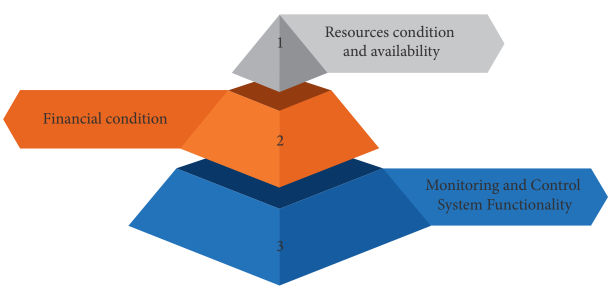


Figure 3: Constraints faced in operation management on the shop floor in industry 4.0.

3. Developed Data-Driven Decision-Making System for Shop Floor Management

The main objective of the data-driven decision-making system is to control uncertain production activities within limited constraints, and it has been possible by the elimination of waste found in production processes on the shop floor. The developed system is an effort to improve the manageability of the shop floor management system to enhance productivity within limited constraints in Industry 4.0.

3.1. Product Information. This case example deals with the improvement in production on a semiautomated assembly line in a leading earthmoving machinery manufacturing unit. This assembly line was dedicated to producing a skid-steer loader. Skid-steer loader is earthmoving machinery and is based on cutting-edge technology. The skid-steer loader is a marvel in the mining machinery industry, complete with maneuverability, compactness, and versatility. The present industry is unable to meet the needs of the customers within the available constraints and is facing continuous customer complaints regarding the quality of the product. This results in dissatisfaction in customers and looking to go to other manufacturers who can provide better mining equipment within the specified time. The actual information of production condition has been collected by Gemba Walk, discussion with workers in meeting, previous records, and direct observation. Table 2 describes previous production records of the shop floor management system.

3.2. Analysis of Shop Floor Management. Lean and smart manufacturing was adopted to investigate the efficiency of the present production management system. A sample case of the earthmoving equipment assembly unit was selected as an example. The production shop floor data have been summarized by an analysis of production factors. A flow chart was developed to understand the actual activities performed on the shop floor. Figure 5 shows production processes performed on the shop floor. The waste related to the production process was identified from the activities being carried out at workstations and by analyzing the production parameters derived from them; the actual state of production was evaluated as was in the proposed methodology. Table 3 describes resources available at the workstation of the present case and it has been analyzed by observation and discussion with workers.

The problems faced by the management system in the present case have been identified by the analysis of resources and actual performance of production processes on the shop floor. To do this, production condition is evaluated by calculating the production parameters and identifying the problems faced on workstations. The production parameters such as lead time (LT), idle time (IT), available time (AT),

Table 1: Description of previous research works according to implemented work methodology.

References	Medium of observation	Analysis of factors	Method	Result
Ramani and Lingan [13]	Survey	Production activities, workload, work plan	Value stream mapping (VSM)	Productivity improvement
Shou et al. [14]	Questionnaire, interview	Production activities, production parameters	VSM	Reduction in production time
Saqlain et al. [15]	Work plan	Production processes, work plan	Internet of things	Productivity enhancement and prognosis of production line
Gijo et al. [16]	Survey	Machinery condition	Lean six sigma	Reduction of cost and defects
Mittal et al. [17]	Survey, interview	Production process, production parameters, work plan	Smart manufacturing	Smart manufacturing able to improve production management system
Stadnicka and Litwin, [18]	Survey	Production process, production parameters, work plan	VSM	Reduction in production time
Asif and Singh [19]	Production activities, work plan	Production processes, work plan	Internet of things	Cost reduction
Cannas et al. [20]	Survey	The production process, machinery condition	Lean manufacturing, Kaizen	Improvement in production time and work performance
Das et al. [21]	Survey	The production process, work plan, production parameter	VSM, Kaizen, single minute exchange of die	Reduction in production time, work-in-process inventory, congestion on the shop floor, and improvement in workplace safety
Chien and Chen [22]	Production activities	Production processes, work plan, machinery	Smart manufacturing	Improved machinery effectiveness, reduced production time
Gaspar et al. [23]	Survey	Production processes, work plan	Internet of things	Proved superior decision-making method
Kumar et al. [24]	Survey, meeting	Production activities, production parameter, work plan, machinery availability	Lean manufacturing, Kaizen	Reduction in production time, manpower, and machinery setting time
Méndez and Rodriguez [25]	Interview, meeting	Production activities, machinery condition, work plan, production parameter	Total productive maintenance	Improvement in productivity and quality
Thomas et al. [26]	Survey, meeting	Production processes, production parameter, work plan	Lean six sigma	Reduction in production time and cost.
Lu and Yang [27]	Survey	The production process, work plan, production parameters, workload	Lean manufacturing, Kaizen	Reduction in production time and improvement in resource utilization
Torres et al. [28]	Survey	Production process, work plan	Smart manufacturing	Smart manufacturing proved an efficient method for shop floor management
Tyagi et al. [29]	Survey, interview, meeting	Production process, work plan, production parameter	VSM	Reduction in production time
Andrade et al. [30]	Survey	Production process, production parameter, workload	VSM	Reduction in production time and improved utilization of work position.
Frankó et al. [31]	Work plan	Production processes on the shop floor	Internet of things	Enhanced efficiency of logistic task
Seth and Gupta [32]	Survey	Production process, work plan, production parameter, workload	VSM	Improvement in production and reduction in work-in-process inventory
Liao et al. [33]	Production processes, work plan	Production activities, machinery condition, work plan,	Internet of things	Reduction in cost and improvement in customer satisfaction in terms of product
Vinodh et al. [34]	Survey, questionnaire	Production process, work plan, production parameter, machinery availability	VSM	Reduction in production time and defects
Beliatis et al. [35]	Work plan, interview	Traceability of the product	Industrial Internet of things	Reduction in bottleneck and lead time
Horak et al. [36]	Work plan	Vulnerability of the production line	Industrial Internet of things	Cyber-attack responsible of malfunction of Internet of things devices and failure of production line

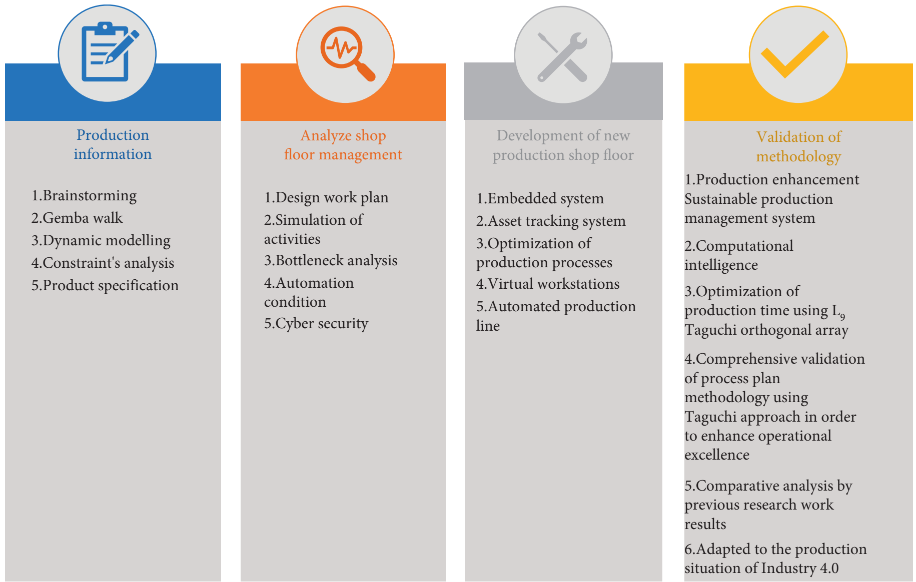


Figure 4: Proposed data-driven system for shop floor management in industry 4.0.

Table 2: Observed production condition on the shop floor.

Production condition	Quantity
Working time	570 minutes
Break time	50 minutes
Available time	520 minutes
Production time	Job shop production
Number of shops	10
Number of product/days	6
Number of processes	18
Number of employees	52
Number of workers	44
Number of shifts	1
Shop floor area	34.5 meter × 76 meter
Material handling equipment	Hoist, forklift
Customer requirement	Time, service, quality, cost
Constraints	Manpower, shop floor area, material handling tool, present shop floor working environment, machinery, budget
Production problems	Higher distance between workstations, breakdown of material handling equipment, lack of production planning, congestion on the shop floor, improper clamping
Process for higher production time	Outsourcing services like painting

uptime (UT), cycle time (CT), change over time (CO), value-added time (VAT), and non-value-added time (NVAT) of production processes have been calculated and shown in Table 4. The problems faced on present production shop floor management system have been described in Table 5.

3.3. Development of New Production Shop Floor. Planning and execution of new production shop floor include four steps according to the working environment: elimination of non-value-added activities, optimization of production processes, proposal of action plan for the elimination of waste, and illustration of production planning a flow chart. The steps refer to improvement in overall production processes on the shop floor. This type of step involves all the optimization of production processes, identification of non-value-added activities, resources, and work plan. The proposed data-driven decision-making system aims to provide a guideline to industry persons for improving production on the shop floor using lean and smart manufacturing. The steps involved in the proposed methodology are shown in Figure 6.

The next step is to develop a workflow chart by optimization of production processes by a suitable method, and the new workflow chart will help the production manager clearly understand the production processes and propose an action plan for the elimination of waste. With all the details of production shop floor management, a workflow sheet has been prepared and presented in Figure 7.

Table 6 shows the proposal of the action plan prepared for smart production shop floor management in all activities.

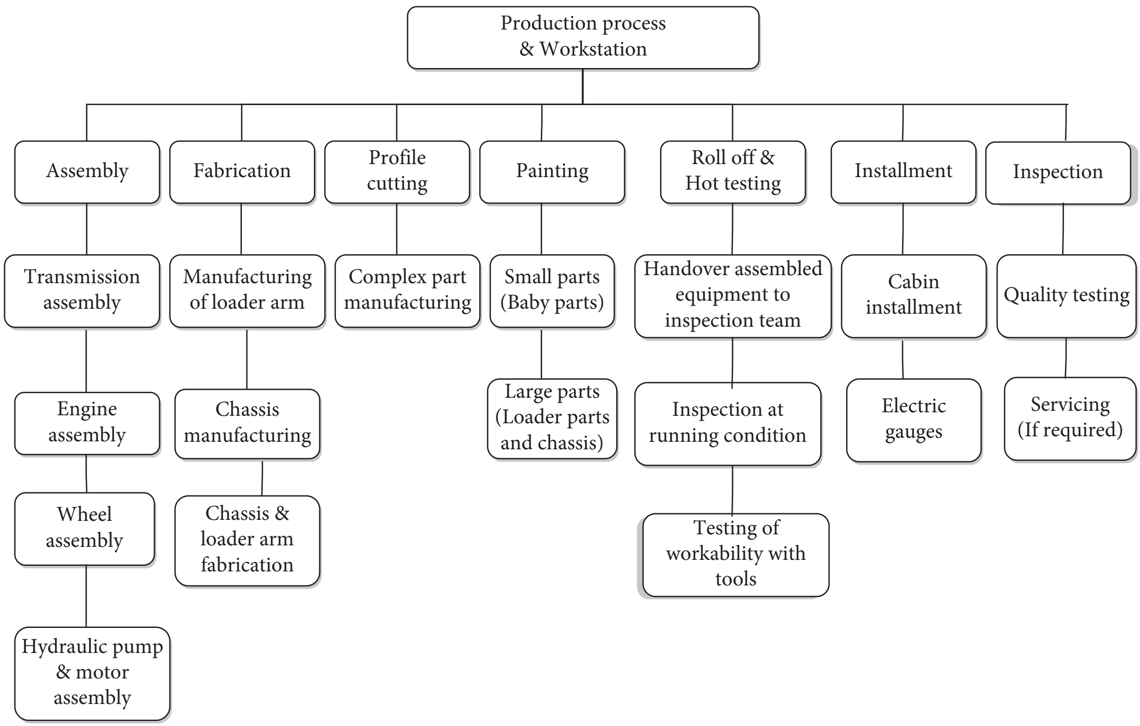


Figure 5: Observed production plan on shop floor.

Table 3: Resource availability on the present production shop floor.

Workstation	Shop floor management method	Resources				
		Manpower	Shop floor area (square meter)	Machinery condition	Machinery position	Material handling equipment
Transmission assembly	Lean manufacturing	4	72.5	Ok	Unplanned	Manual
Engine assembly	Lean six sigma	2	18.7	Poor	Planned	Manual
Wheel assembly	Smart manufacturing	2	16.36	Ok	Planned	Manual
Hydraulic pump assembly	Lean manufacturing	2	12.53	Ok	Unplanned	Manual
Hydraulic motor assembly	Lean manufacturing	2	12.53	Ok	Unplanned	Manual
Manufacturing of loader arm	Lean manufacturing	3	71.23	Ok	Planned	Hoist
Chassis manufacturing	Lean manufacturing	5	45.99	Poor	Unplanned	Manual
Chassis and loader arm fabrication	Lean six sigma	3	56.125	Insufficient	Unplanned	Forklift
Complex part manufacturing	Smart manufacturing	1	113.94	Ok	Planned	Hoist
Painting (baby part)	Lean manufacturing	2	89.02	Ok	Planned	Hoist
Painting (loader and chassis)	Lean six sigma	Outsourcing	72.5	Not available	Not available	Forklift
Handover of equipment to the inspection team	Lean manufacturing	2	72.5	Not required	Not required	Manual
Inspection at running condition	Lean manufacturing	4	837.47	Not required	Not required	Not required
Testing of tools workability on field	Lean manufacturing	4	72.5	Ok	Planned	Manual
Cabin installment	Smart manufacturing	2	110.800	Malfunctioning	Planned	Hoist
Electric gauge assembly	Lean manufacturing	2	89.04	Ok	Planned	Manual
Quality inspection	Lean six sigma	2	135.66	Ok	Unplanned	Not required
Servicing	Lean manufacturing	2	Not required	Ok	Unplanned	Manual

Table 4: Analysis of present production processes on the shop floor.

S.No.	Process	AT (minute)	UT (%)	No. of operators	CO (minute)	CT (minute)	NVAT (minute)	IT (minutes)
1	Transmission assembly	520	82.69	8	90	360	105	15
2	Manufacturing of loader arm	520	87.50	3	65	245	95	30
3	Chassis manufacturing	520	85.58	4	75	265	140	65
4	Wheel assembly	520	97.12	3	15	150	25	10
5	Chassis and loader arm fabrication	520	79.81	3	105	300	150	45
6	Inspection of fabrication	520	97.12	3	15	60	45	30
7	Painting (baby parts)	520	95.19	2	25	315	55	30
8	Painting (large parts)	520	90.38	1	50	300	1490	1440
9	Engine assembly	520	93.27	2	35	190	50	15
10	Hydraulic pump and motor assembly	520	95.19	2	25	120	45	20
11	Roll off and hot testing	520	89.42	6	55	2370	165	110
12	Cabin installment	520	96.15	2	20	185	60	40
13	Electric gauges assembly	520	95.19	3	25	195	70	45
14	Final inspection	520	98.08	2	10	160	35	25

Table 5: The problems faced by the management system in production processes.

S.No.	Name of shop	Problems	Source of problem
1.	Transmission	1. Long-distance between workstations 2. Unplanned location of machinery 3. Lack of material handling equipment 4. Lack of safety on the shop floor 5. Improper workload	(i) Lack of workload allotment (ii) Ergonomics issues (iii) Absence of condition monitoring system (iv) Lack of production planning
2.	Fabrication	1. Workplaces are not decided 2. More workstations 3. Lack of fabrication plan 4. Lack of fabrication equipment	(i) Inefficient production workflow (ii) Lack of layout
3.	Profile cutting	1. Mostly shutdown. 2. Higher setup time 3. Rarely required 4. Lack of skilled workers	(i) Absence of smart control system (ii) Lack of awareness
4.	Engine assembly	1. A longer distance between workstations 2. Higher material handling time 3. Lack of workers 4. Poor arrangement for material handling	(i) Safety issues (ii) Manual power control system (iii) Lack of work allotment plan
5.	Painting	1. Painting of larger parts has been done in another plant 2. Required extra worker for inspection of larger part painting 3. Fewer number of workers in the painting shop 4. Ergonomics issues	(i) Outsourcing of services (ii) Logistics issues (iii) Traditional safety equipment (iv) Congestion at the workstation
6.	Hot testing	1. No timeline set for the workstation 2. Due to the lack of shop floor area at the next workstation, the movement time of the product is not determined	(i) Lack of work plan (ii) Parking in open space due to shortage of area on the shop floor
7.	Cabin installment	Lack of worker's experience Malfunctioning in machinery	(i) Lack of training and meetings (ii) Manual control system
8.	Electric gauge assembly	1. Lower worker skills 2. Higher workload	(i) Worker's involvement in more than one shop (ii) Lack of workload plan
9.	Quality inspection	1. Non-detection of faults 2. Unnecessary change of workers	(i) Manual inspection (ii) Lack of workload plan

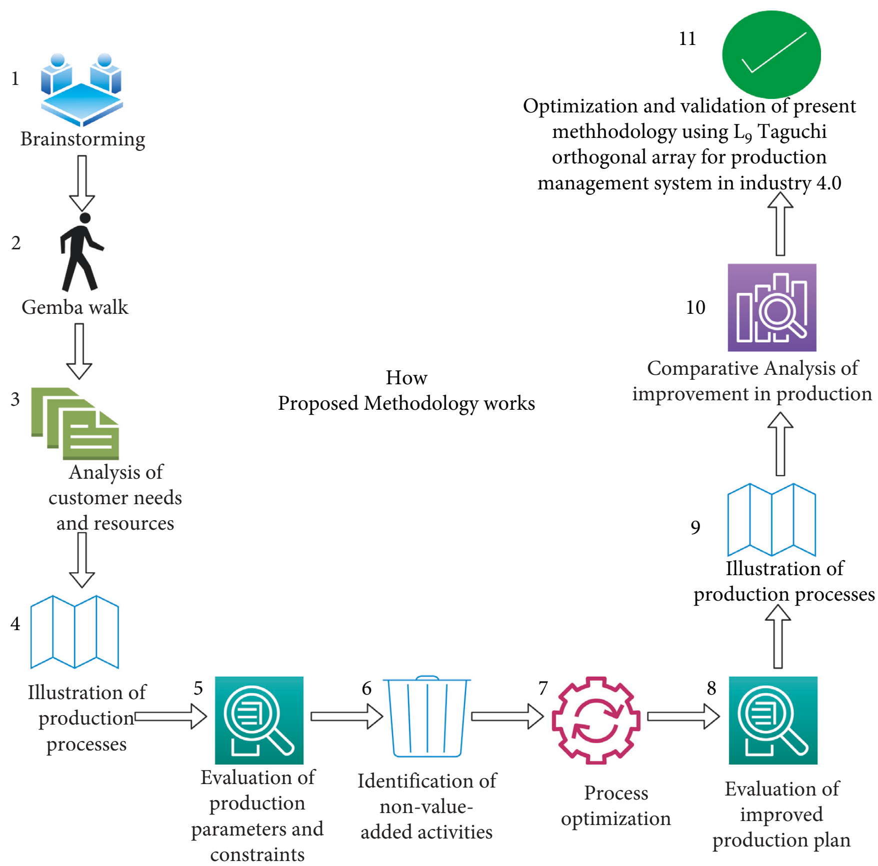


Figure 6: Modified production plan.

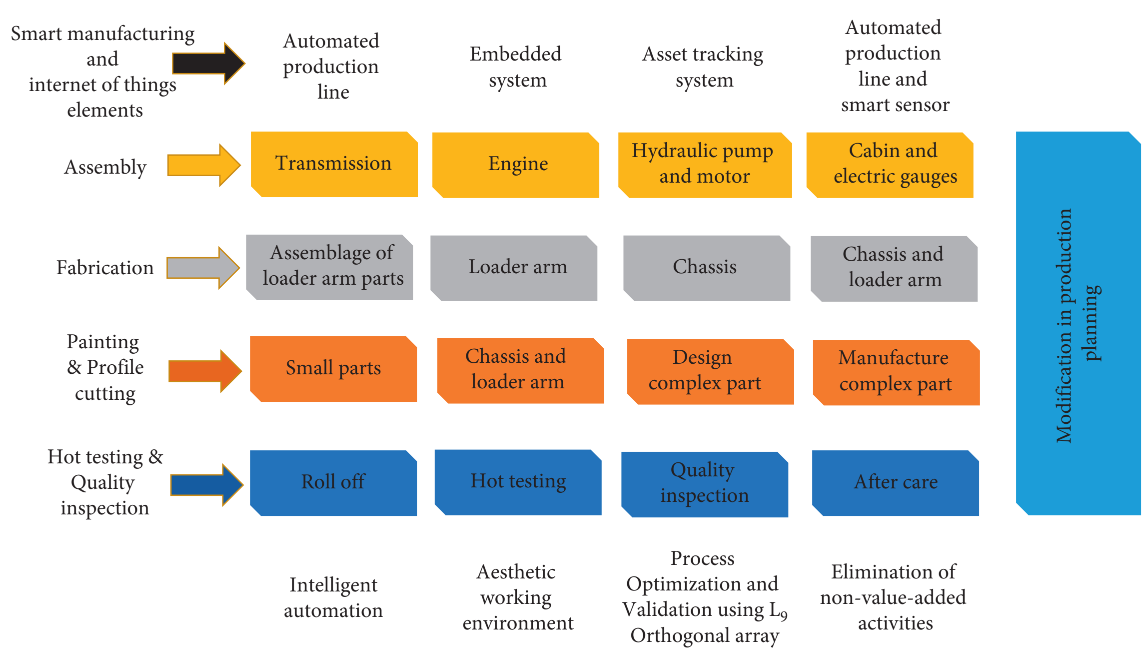


Figure 7: Modified new production management system.

Table 6: Proposed action for production planning.

S. No.	Name of shop	Proposed action	Non-value-added activity	Suggested smart production management system	Process optimization
1.	Transmission	(i) Reduced distance between workstations (ii) Machinery placed at the planned location (iii) Provide material handling equipment (iv) Followed up safety norms on the shop floor (v) The workload has been decided according to the skill of the workers	Transportation, inventory, motion, non-utilized talent	Automated production line	Yes
2.	Fabrication	(i) Decided workload according to the skill of the workers (ii) Reduced number of workstations (iii) Developed fabrication planning (iv) Arranged fabrication equipment in a systematic manner	Non-utilized talent, motion, waiting, defect	Embedded system	Yes
3.	Profile cutting	(i) Organized training for operators (ii) Eliminate unnecessary activities	Non-utilized talent, motion	Embedded system	NA
4.	Engine assembly	(i) Improvement in layout (ii) Reduced distance between workstations (iii) Increased number of workers (iv) Arranged material handling equipment in a proper manner	Transportation, inventory, motion, non-utilized talent, excess processing	Automated production line	Yes
5.	Painting	(i) Increased number of workers (ii) Provided safety equipment for workers (iii) Both the processes were started simultaneously	Motion, waiting, overproduction	Embedded system	Yes
6.	Hot testing	(i) Decided timeline on the workstation (ii) Increased shop floor area in layout	Motion	Embedded system, asset tracking system	Yes
7.	Cabin installment	(i) Organized meetings and training	Excess processing, motion	Automated production line, embedded system	Yes
8.	Electric gauge assembly	(i) Replaced operator by skilled operator (ii) Decided workload distribution	Excess processing, non-utilized talent, inventory	Embedded system	Yes
9.	Quality inspection	(i) Improve production planning (ii) Eliminate unnecessary activities	Motion, excess processing	Automated production line	Yes

After the review of the production management system, it has been decided that which workstation and production process needed to improve. The review process was done by production workflow analysis session and evaluation of production parameters. The calculation of each parameter used in production shop floor management has been discussed in Table 7.

4. Results and Discussion

4.1. Development of the Current System in Order to Enhance the Operational Performance by Using Hybrid Integrated Lean and Smart Manufacturing Methodology. In line with the research, the objective raised the result demonstrated non-value-added activities and production time reduction and

Table 7: Improvement in production parameter in product.

S. No.	Process	AT (minute)	UT{UT = (AT – CO)/AT)} (%)	Number of workers	CO (minute)	CT (minute)	NVAT (minutes)	Idle time (minutes)
1	Transmission assembly	520	85.58	7	75	340	85	10
2	Manufacturing of loader arm	520	88.46	4	60	245	80	20
3	Chassis manufacturing	520	86.54	5	70	250	130	60
4	Wheel assembly	520	98.08	3	10	135	20	10
5	Chassis and loader arm fabrication	520	79.81	5	105	320	160	45
6	Painting	520	90.38	2	50	240	1470	1420
7	Engine assembly	520	93.27	3	35	180	50	15
8	Hydraulic pump and motor assembly	520	96.15	3	20	120	40	20
9	Roll off and hot testing	520	91.35	7	45	2310	135	90
10	Cabin installment and electric gauge assembly	520	94.23	3	30	330	75	45
11	Final inspection	520	98.08	2	10	150	30	20

provided benefits in production improvement within limited constraints through the proposed methodology using the shop floor management method for the mining machinery assembly unit in Industry 4.0. In this production management application study, production time reduction was successfully achieved by reducing the waste by facing the challenges of complex environments of the production shop floor. Authors used a new methodology on production shop floor conditions, logically followed only production workflow which does not get into the concept of production management methods, like production parameters, production factors within limited contraints which have been promoted by the previous researchers. The study reports overall production time reduction within available constraints on the production shop floor. To know actual improvement achieved by proposed methodology implementation, an analysis has done between previous condition and improved condition of the production shop floor. The analysis of production enhancement has been shown in Table 8.

The similar results have been found out by Dehghani et al. [37], who proposed a new game-based optimization algorithm named dart game optimizer. The quality and ability of the performance of dart game optimizer was checked by twenty-three objective functions and was compared with other eight optimization algorithms, including particle swarm optimization, genetic algorithm, gravitational search algorithm, grey wolf optimizer, teaching learning-based algorithm, grasshopper optimization algorithm, marine predators algorithm, and whale optimization algorithm. The result of the study showed that the developed algorithm was efficient and able to exploit and explore in solving different optimization problems. Dehghani et al. [38] developed a new optimizer named multileader optimizer to solve optimization problems. The designed optimizer was used to conduct the algorithm toward a quasi-optimal solution by using information from population members. The result of the study showed that the developed algorithm was superior in solving optimization problems. Dehghani et al. [39] developed a binary model of orientation search algorithm named binary orientation search algorithm. The twenty-three benchmark test functions tested the developed model. The result of the study showed that the developed model was able to solve optimization problems efficiently.

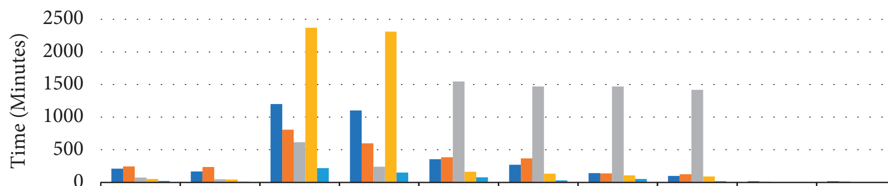
Dehghani et al. [40] developed a spring search algorithm to solve single-objective constraints optimization problems. The functionality of the developed algorithm was evaluated by thirty-eight established test mark functions and compared with other eight optimization algorithms, including a teaching learning-based algorithm, genetic algorithm, gravitational search algorithm, grasshopper optimization algorithm, particle swarm optimization, a spotted hyena optimizer, a grey wolf optimizer, and emperor penguin optimizer. The result of the study showed that the developed algorithm has superior exploitation and exploration capabilities compared to other algorithms.

The proposed methodology has been efficiently implemented in the present case example of Industry 4.0, in which systematic work planning has been helpful for the reduction in congestion on the shop floor and results in productivity enhancement. Productivity improvement on the shop floor in terms of production parameters has been shown in Figure 8.

The similar results have been reported by Dhiman and Kumar [41], who developed a metaheuristic algorithm called spotted hyena optimizer. The developed algorithm was implemented to one unconstrained engineering design problem and five real-life constraints and compared with eight algorithms on twenty-nine benchmark test functions. The result of the study demonstrated that the developed algorithm was better than other metaheuristic algorithms. Dhiman and Kaur [42] developed a bio-inspired algorithm named sooty tern optimization algorithm for constrained industrial problems. The developed algorithm was implemented to solve six constrained industrial applications and compared with nine algorithms over forty-four benchmark functions. The result of the study revealed that the developed model was able to solve constrained problems and was efficient in comparison to other algorithms. Kaur et al. [43] proposed a bio-inspired algorithm named tunicate swarm algorithm. The performance of the tunicate swarm algorithm

Table 8: Analysis of improvement in terms of production parameter and utilization of resource.

Name of shop	Production parameters					Utilization of resource		
	CT (minutes)	CO (minutes)	IT (minutes)	NVAT (minutes)	UT (%)	No. of worker	Machinery	Shop floor area (square meter)
Assembly	45	25	5	30	3.97	2	Yes	224.9
Fabrication	305	95	105	190	12.56	2	Yes	0
Painting	375	25	50	20	4.35	0	NA	89.1
Roll off and hot testing	60	10	20	30	1.76	1	NA	837.5
Installment	50	15	40	55	2.71	2	Yes	110.8
Inspection	10	0	5	5	0	3	Yes	0



	CO (P1)	CO (P2)	CT (P1)	CT (P2)	NVAT (P1)	NVAT (P2)	IT (P1)	IT (P2)	Worker (P1)	Worker (P2)
Assembly	210	170	1200	1105	355	270	145	100	20	19
Fabrication	245	235	810	600	385	370	140	125	10	14
Painting	75	50	615	240	1545	1470	1470	1420	3	2
Hot testing	55	45	2370	2310	165	135	110	90	6	7
Quality inspection	25	10	220	150	80	30	55	20	5	2

Figure 8: Analysis on parameter between present and proposed shop floor (P1-observed shop floor condition, P2-modified shop floor condition).

was evaluated on seventy-four benchmark test problems by ANOVA test. The result of the study revealed that the developed algorithm was able to provide a better optimal solution compared to other algorithms. Dhiman and Kumar [44] developed an optimization algorithm called emperor penguin optimizer. The performance of the developed algorithm was evaluated on forty-four benchmark test functions by implementing seven nonlinear and mixed-integer structural problems. The result of the study demonstrated that the developed algorithm was able to provide better results than other metaheuristic problems. Dhiman and Kumar [45] proposed a bio-inspired algorithm named seagull optimization algorithm. The performance of seagull optimization algorithm was compared with forty-four benchmark functions. The result of the study revealed that the developed algorithm was able to solve large-scale constrained problems and was efficient in comparison to other optimization algorithms.

Due to the problems encountered in production shop floor management, the present case study shows the elimination of waste and the improvement in productivity levels that have been possible through the proposed system. To substantiate this statement, a comparative analysis was performed on the present research work with previous research works. It was found from the analysis that the proposed methodology is superior in the elimination of each production problem and non-value-added activities in Industry 4.0. The comparative analysis on some important production conditions between previous researches and the present study has been shown in Table 9.

The related work has been revealed by Dhiman et al. [46], who developed a metaheuristic algorithm named emperor penguin optimizer. Twenty-five benchmark functions validated the output of the developed algorithm. Furthermore, the result of the study demonstrated that the developed algorithm was superior in comparison to other algorithms. Dhiman [47] developed a bio-inspired metaheuristic optimization approach named emperor penguin and salp swarm algorithm. The efficiency of the developed algorithm was evaluated by convergence analysis, scalability analysis, ANOVA test, and sensitivity analysis. The result of the study revealed that the developed algorithm was superior and provided optimal solutions compared to other algorithms. Dhiman et al. [48] developed a bio-inspired optimization algorithm named rat swarm optimizer to solve optimization problems. In the study, the performance of the developed algorithm was validated by comparing it with eight optimization algorithms. The result of the experiment revealed

Table 9: Benefits of the proposed methodology in comparison of previous methodologies.

Industry condition	Previous methodologies			Proposed methodology	
	Authors	Changes	Status	Changes	Status
Production capacity	[25]	10.7%	Improved	66.67%	Improved
Production cost	[5]	40%	Improved	46%	Improved
Production lead time	[34]	1.07%	Improved	11.10%	Improved
Manpower requirement	[36]	26.08%	Improved	34.09%	Improved
Utilization of machinery	[25]	8.9%	Improved	16.67%	Improved
Shop floor utilization	[21]	NA	Improved	33.55%	Improved
Reduction of defects	[16]	85.26%	Improved	88.89%	Improved
Setup time reduction	[24]	65.85%	Improved	72.37%	Improved
Working environment	[21]	NA	Improved	Safety, working time, workload	Improved

that the developed algorithm was efficient in solving real-world optimization problems. Vaishnav et al. [49] performed a logical analysis on total death, total cases, and total recovery reported in the pandemic of COVID-19. In the study, decision tree regression and random forest models were used to perform logical analysis. The result of the study revealed that the prediction accuracy of the random forest model and a regression model was 76% and 70%, respectively.

After a comparison of the proposed data-driven decision-making system with previous research works as suggested in the literature, it has been concluded that majorly three drawbacks were found in previous systems. The drawbacks included the inability to produce within limited resources, giant gaps in resource utilization, and poor working conditions on the production shop management. The present article proposed a data-driven decision-making system that pays attention to these drawbacks. The proposed methodology was proved superior by productivity enhancement obtained in results within limited constraints in Industry 4.0. The comparison between results obtained by the previous methodology and presented methodology as discussed in Table 8 revealed that the proposed system is able to provide superior results within limited constraints in Industry 4.0.

4.2. Implementation of L_9 Taguchi Orthogonal Array to Reduce Production Time. The management teams were curious to optimize production processes in the present industry for operational enhancement because they were facing several problems in production management, including higher cycle time, inefficient workers, higher downtime, and excess power consumption. In the present work, brainstorming sessions have been organized with team members and workers to recognize the exact reason for problems in the production processes on the shop floor. Brainstorming sessions have concluded that the main reasons for the problem were the excess movement of workers due to lack of workload distribution, breakdown of material handling equipment due to lack of planning, shop floor congestion, disarrangement of machinery, outsourcing, and lack of monitoring system. Therefore, three parameters, including cycle time, number of operators, and available time, influenced operational performance on the shop floor. In the study, Minitab is used to design experiment-based Taguchi method considering three parameters with three levels in which level 1 is lowest and 3 is highest (Table 10).

Analysis of variance is used to identify the relative significance of the individual production parameters as illustrated in Table 11. The table can conclude that the idle time, cycle time, and non-value-added time reduction have contributed efficiently.

ANOVA proved that number of operators is the most significant parameter effecting the production time and it contributes 74.78% to obtain minimum production time. Available time is also another significant parameter, and its contribution is 22.40%, while cycle time is insignificant. Table 12 shows the model summary.

The operational performance of production processes is analyzed by Taguchi's L_9 orthogonal array method and expressed in signal-to-noise ratio. This analysis is performed to obtain the precise operational setting for production time on the Industry 4.0 shop floor. Tables 13 and 14 illustrate the response table for the signal-to-noise ratio (smaller is better) and the means. Figures 9 and 10 show the analysis found on the signal-to-noise ratio.

Response table for S/N ratio and means signifies that no. of operators is the important factor that effects production time followed by available time and cycle time.

Main effects plot for production time reveals that available time of 520 minutes, cycle time of 5260 minutes, and number of operators of 44 yield minimum production time.

4.3. Validation of Methodology. The results of validation are compared with the estimated with the optimum production parameters. Minimum production time could be obtained at available time of 520 minutes, cycle time of 5260 minutes, and number of operators of 44 based upon the response plots as shown in Figures 5 and 6 of production time analysis. This indicate that the obtained optimal setting of controllable factors for available time, cycle time, and number of operators results in the lower production time. As a result, Taguchi validation method as great potential application in highly competitive mining machinery shop floor industry due to its reliability and predictive accuracy in managing the process operating factors and limited number of trial experimentation required, which saves time, effort, and

Table 10: Experimental data used for the analysis.

Available time (mins)	No. of operators	Cycle time (mins)	PT (mins)	SNRA3
490	43	5245	7820	−77.8641
490	44	5260	8510	−78.5986
490	45	5280	7544	−77.552
520	43	5260	8280	−78.3606
520	44	5280	8832	−78.9212
520	45	5245	8004	−78.0661
560	43	5280	7590	−77.6048
560	44	5245	8510	−78.5986
560	45	5260	7590	−77.6048

Table 11: Analysis of variance.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage contribution
Available time (mins)	2	0.46562	0.46562	0.232809	47.84	0.020	22.40%
No. of operators	2	1.55439	1.55439	0.777196	159.69	0.006	74.78%
Cycle time (mins)	2	0.04896	0.04896	0.024481	5.03	0.166	2.36%
Residual error	2	0.00973	0.00973	0.004867			0.47%
Total	8	2.07871					

Table 12: Model summary.

S	R-Sq	R-Sq (adj)
0.0698	99.53%	98.13%

Table 13: Response table for signal-to-noise ratios.

Level	Available time (mins)	No. of operators	Cycle time (mins)
1	−78.00	−77.94	−78.18
2	−78.45	−78.71	−78.19
3	−77.94	−77.74	−78.03
Delta	0.51	0.97	0.16
Rank	2	1	3

Table 14: Response table for means.

Level	Available time (mins)	No. of operators	Cycle time (mins)
1	7958	7897	8111
2	8372	8617	8127
3	7897	7713	7989
Delta	475	905	138
Rank	2	1	3

resources. As far as optimization and plan validation is concerned, the production time has been optimized by using L_9 Taguchi orthogonal array by considering available time, cycle time, and number of operators as input parameters. This novel process optimization methodology has been strongly recommended to detect, mitigate, and eliminate the production uncertainties and non-value-added activities within available resources in order to achieve vital progressive objectives of Industry 4.0.

A smart system should monitor some types of validations (constraints, resource conditions, workload distribution, workflow flexibility, shop floor capability, etc.). As discussed above, each type of validation is related to production efficiency or operational excellence on the shop floor [50]. Production efficiency means that the desired production process parameters can be improved by maximizing resources. At the same time, operational excellence demonstrates that eliminating waste can improve the desired production process parameter. The types of validations should be evaluated to investigate the production system's actual effectiveness and significant for the improvement in production efficiency and elimination of waste [51].

The developed system has been implemented to optimize production processes and identify waste. The proposed data-driven decision-making system uses the lean and smart manufacturing concept to execute production planning on the shop floor. Production evaluation shows that the production system has improved in terms of productivity level, floor layout, safety, production time, working environment and worker efficiency. The validation of the proposed methodology involves four levels of action according to the present industrial working environment: analysis of production enhancement in terms of production parameter and utilization of resources; comparison of improvement on the shop floor in terms of production conditions; comparative analysis between proposed system and previous system as suggested in previous research work; and validation of methodology by analysis of improvement achieved in production. These levels help validate the proposed methodology and can give the management system confidence that it can provide improvements in the production system with increased productivity in Industry 4.0. Figure 11 describes improvement obtained on the production shop floor in terms of production parameter within available resources, and it validates that the proposed methodology will be helpful for the production management system in Industry 4.0.

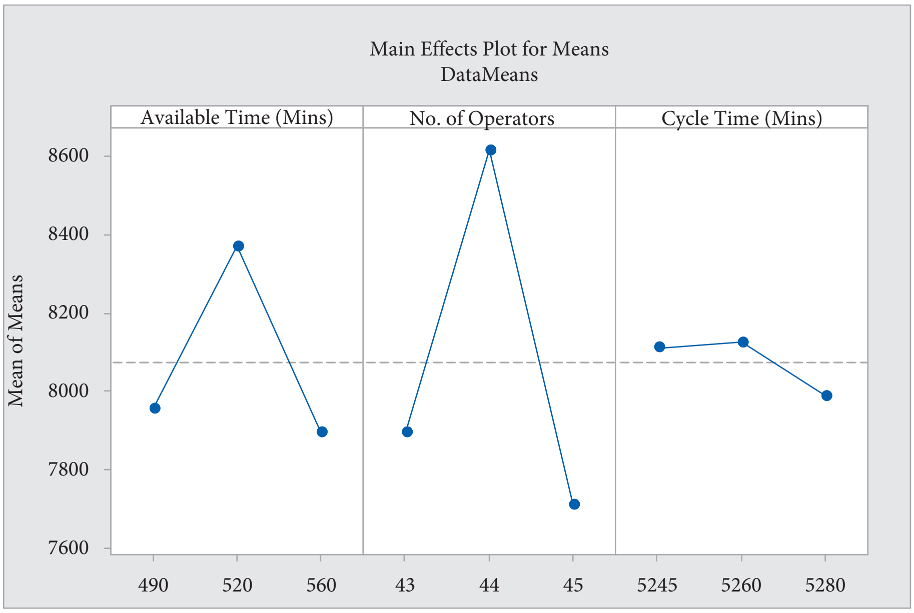


Figure 9: Main effect plot for production time.

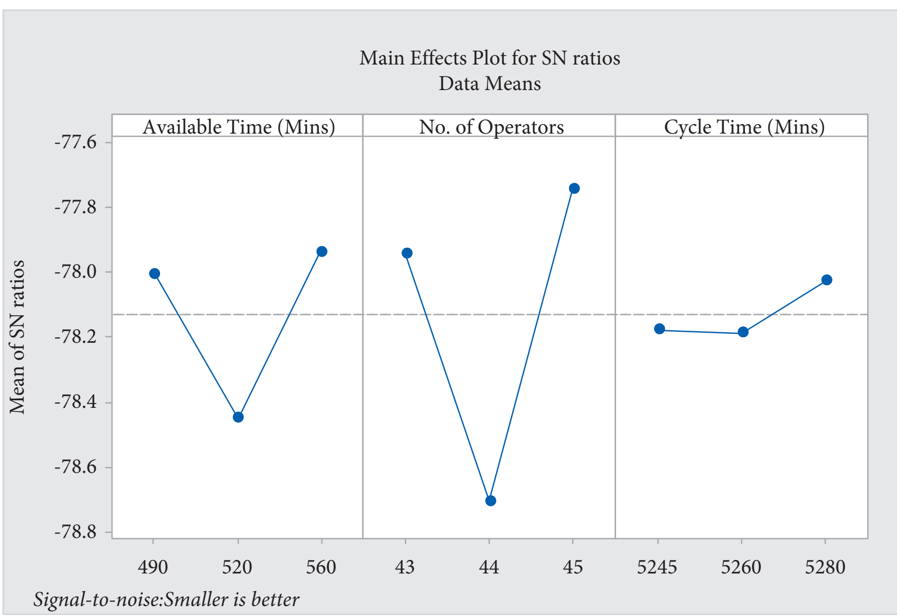


Figure 10: Signal-to-noise ratio for production time.

5. Notable Contributions of Lean and Smart Manufacturing Concept in Industry 4.0

The production management team members emphasize developing a decision-making system to enhance operational excellence in complex manufacturing environments, including Industry 4.0, using process optimization methods. Various process optimization methods that have been used in previous research work for shop floor management include smart manufacturing, artificial neural network, lean manufacturing, Internet of things, and cyber-physical system. In an extensive literature review, it has been found that the researchers and industry individuals preferred to implement lean manufacturing concept on the shop floor, but industrial revolutions and changes have led to a demand for new methods in shop floor management. The researchers focus on developing a hybrid method for operations management on the shop floor to accomplish this. The hybrid method uses the integration of two or more methods to enhance the adaptability of operational excellence in production processes on the shop floor. Lean and smart manufacturing concepts works as hybrid method and fulfil this need of the industry individuals to enhance productivity within limited constraints. Implementing lean manufacturing in the shop floor management, including Industry 4.0, can effectively improve operational excellence when

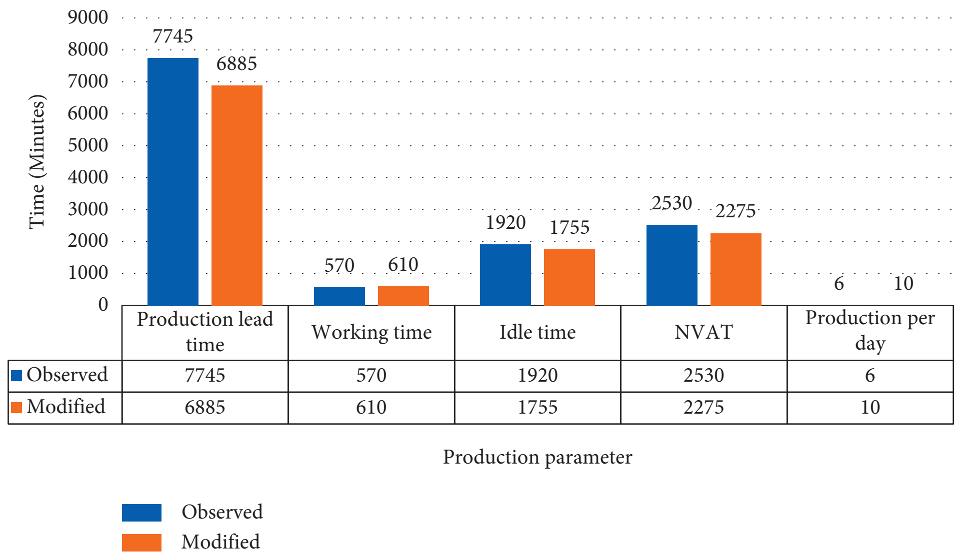


Figure 11: Improvement obtained in production parameters.

integrated with the smart manufacturing concept. Ghobakhloo and Ching [52] discussed the identification of determinants of smart manufacturing-related information and digital technologies. The data for analysis were collected from an electronic survey and questionnaire organized in Malaysian and Iranian small and medium enterprises. The results showed that smart manufacturing-related information and digital technologies were costly for most small and medium enterprises and significantly influenced by the imposition from the environment. Tripathi et al. [53] developed an agile system to improve operational performance using a methodology coupled with VSM. The developed method was validated by improving the operating performance of a production management system in Industry 4.0 environment. Furthermore, the result of the study revealed that the developed system was able to enhance operational excellence by eliminating waste within available resources in Industry 4.0.

Li [54] developed a conceptual model using lean, smart manufacturing and implemented it in the bicycle industry. The result of the study demonstrated that lean and smart manufacturing could enhance operational excellence of the management system by setting up a smart factory platform in Industry 4.0. Dey et al. [55] proposed smart chain management for imperfect production processes where demand rate was variable and demand depended on the advertisement. The study developed a mathematical model to identify imperfect items in production processes for making more innovative processes. The results revealed that the developed model could help managers reduce total costs and enhance system profit. Chiarini and Kumar [56] investigated on the integration of Industry 4.0 technologies and lean six sigma. The analysis has been done by direct observations and interviewing experts and managers of ten Italian manufacturing industries. The result demonstrated that lean six sigma could enhance outcomes effectively by using Industry 4.0 technologies. Amjad et al. [57] developed a framework for integration of green manufacturing, lean manufacturing, and Industry 4.0 in harmonious way. The framework was validated by implementing in an auto-parts manufacturing industry. The result of the study demonstrated that the developed framework was efficiently optimized and reduced the lead time, value-added time, greenhouses gas emission, and non-value-added time emission effectively by 25.60%, 24.68%, 55%, and 56.20%, respectively.

It has been observed that the hybrid methods attract the attention of researchers in operation management on the shop floor because of the enhancement of operational excellence within limited constraints [4, 12, 16, 24, 26, 47, 56, 58]. The present research work focuses to develop a data-driven decision-making system using lean and smart manufacturing for smart and safer shop floor management. The developed system has been validated by implementing it in an actual production condition for the shop floor management. The study revealed that the developed data-driven decision-making system enables the shop floor management teams to enhance productivity and industrial sustainability by eliminating waste within available resources in Industry 4.0. Figure 12 demonstrates the benefits of the developed data-driven decision-making system compared to previous research outcomes regarding standardized factors of the shop floor management system.

Lean and smart manufacturing is a prevalent approach for operation management on the shop floor and it is used to enhance operational performance by optimization of processes and elimination of waste. Lean and smart concept helps industry individual in improvement in operational control on the shop floor by understanding and analyzing actual production condition. The management teams use various standard parameters to evaluate the observed production system using lean and smart manufacturing. The parameters include available time, uptime, worker, changeover time, cycle time, idle time, and non-value-added time.

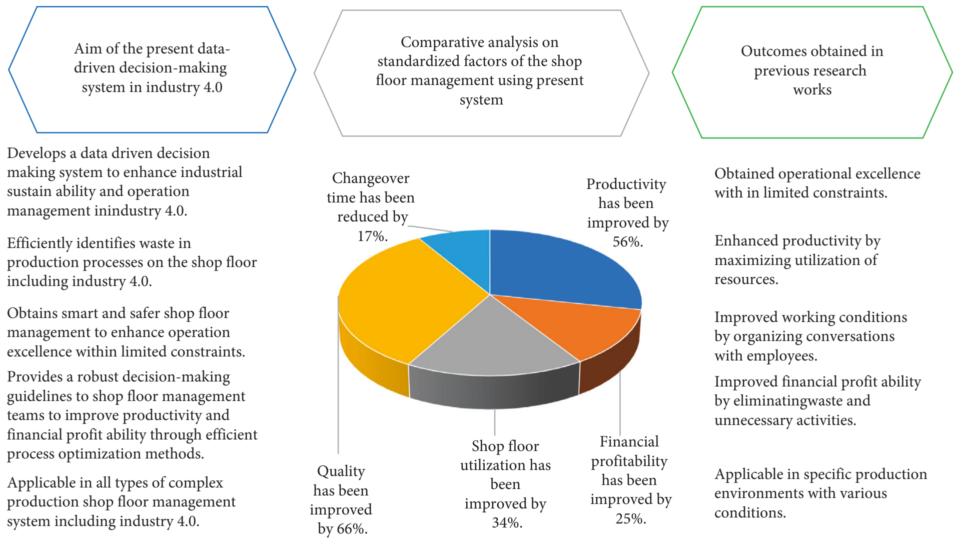


Figure 12: Description of benefits of the developed system in comparison with findings of previous research works.

In previous research works, it has been observed that available time has been calculated by finding the difference between total working hours and break time; uptime is measured as the difference between available time and changeover time and the ratio between their available time; the number of operators has been calculated by observing allotment of workers at each workstation; change over time has been computed by observing time taken for changing time between two processes including setup time; cycle time has been calculated by completion time of each process; the non-value-added time has been computed by the sum of changeover time and idle time; and idle time has been measured by observing the time in which no any activity performed. These parameters are used to investigate the actual performance of the shop floor management system. The researchers and management teams used all the parameters in previous research works to identify the primary source of the problem. The parameters help industry individuals to understand and control production processes by implementing a robust action plan.

Ramani and Lingan [13] improved the performance of the production management system by implementing value stream mapping in an industry of gas-insulated switchgear design. Value stream mapping is a lean-based method to enhance productivity by eliminating waste. The management team members drew an actual shop floor diagram using the value stream mapping principle to identify and eliminate sources of waste. Results showed a 30% improvement in productivity and a 30% reduction in man-hours. Sutharsan et al. [59] examined the application of the lean concept in the Monoblock pump industry using value stream mapping. Value stream mapping improved the workflow chart diagram of production processes by eliminating waste by calculating parameters including available time, lead time, value-added time, and cycle time. The study showed a reduction in lead time, cycle time, and defect rate by 1.4 days, 12.8 minutes, and 2%, respectively. Sahoo et al. [5] developed a systematic strategy to implement Taguchi's method's lean concept. The developed strategy was implemented in a forging industry for improvement in operational performance by the elimination of waste. The study's result revealed a significant reduction in non-value-added activities, shop floor area, and lead time by 72 minutes, 27%, and 325 minutes, respectively. Tripathi et al. [60] developed a model for shop floor management using an artificial neural network coupled with value stream mapping. The developed model was implemented in an earthmoving equipment machinery manufacturing unit. In the study, value stream mapping was used to enhance operational performance by eliminating waste. In addition, various parameters were analyzed, including available time, uptime, cycle time, uptime, non-value-added time, and the number of workers, to understand the present production shop floor condition. The developed model was machine learning-based and tested by proposed shop floor management. The result of the study revealed that the developed model was efficient for prediction purposes with mean absolute error and mean square error.

6. Conclusions

In the present research article, a methodology has been developed for robust regulation of shop floor management in uncertain production conditions in Industry 4.0. It has been observed that lean and smart manufacturing is able to control uncertain production conditions on the shop floor in Industry 4.0. The proposed data-driven decision-making system enables the management team to enhance productivity and industrial sustainability within limited constraints in Industry 4.0. From the reported result, it was observed that the proposed system significantly improved the efficiency of production management and operational performance by suggesting smart systems. The results of the study showed that a substantial reduction in production time and cost has been achieved. In this article, the authors suggested an ingenious methodology that allows a simultaneous optimization and process parameter validation that is production time by using Taguchi approach in order to provide more flexibility and productivity efficiency for shop floor management in Industry 4.0. Based on the results obtained under validation of Taguchi method, ANOVA results evidenced that number of operators is the most significant parameter effecting the production time and it contributes 74.78% to obtain minimum production time. Available time is also another significant parameter, and its contribution is 22.40%, while cycle time is insignificant. The developed data-driven decision-making system would be a benchmarking and problem-solving for enhancement in productivity and provide a smart production management system using lean and smart manufacturing principles in Industry 4.0. The authors of the present research work strongly believe that the developed system would be beneficial to industry individuals in the smart production shop floor management system in the uncertain condition in Industry 4.0. The study helps control operational excellence by reducing waste and idle time through the Taguchi L_9 orthogonal array method and enhancing its effectiveness using lean and smart manufacturing. Thus, we can suggest that the advanced Taguchi approach could be applicable for industrial environments at optimal production process parameter with high-quality statistical design to enhance the operational excellence. Furthermore, the finding can be used for those production conditions where the production time and resources consumption increase due to excessive changes in adjustments of production processes.

7. Future Scope

The implementation of an appropriate strategy is a crucial decision for shop floor management. Therefore, industry people emphasize developing a robust decision-making system and guidelines to make this decision right [6, 9, 16, 26, 53, 56, 58, 60, 61]. The present research focuses on developing a data-driven decision-making system for sustainable shop floor management using lean and smart manufacturing concepts. The developed system has been validated by implementing it in a real production shop floor management condition of Industry 4.0. The result revealed that the developed system could enhance production efficiency and financial profitability within limited constraints. Furthermore, the developed decision-making system's efficacy can be improved by implementing lean principle with other process optimization methods for shop floor management in different production conditions, including Industry 4.0.

Data Availability

The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] W.-H. Tsai and Y.-H. Lu, "A framework of production planning and control with carbon tax under Industry 4.0," *Sustainability*, vol. 10, no. 9, p. 3221, 2018.

[2] J. A. Garza-Reyes, V. Kumar, S. Chaikittisilp, and K. H. Tan, "The effect of lean methods and tools on the environmental performance of manufacturing organisations," *International Journal of Production Economics*, vol. 200, pp. 170–180, 2018.

[3] V. Tripathi, S. Saraswat, and G. D. Gautam, "A study on implementation of various approaches for shop floor management," *Advances in Energy Technology*, Springer, Berlin, Germany, 2021pp. 371–387, Lecture Notes in Electrical Engineering.

[4] V. Tripathi, S. Chattopadhyaya, A. K. Mukhopadhyay et al., "An innovative agile model of smart lean-green approach for sustainability enhancement in Industry 4.0," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 7, p. 215, 2021.

[5] A. K. Sahoo, N. K. Singh, R. Shankar, and M. K. Tiwari, "Lean philosophy: implementation in a forging company," *International Journal of Advanced Manufacturing Technology*, vol. 36, no. 5-6, pp. 451–462, 2008.

[6] V. Tripathi, S. Saraswat, and G. D. Gautam, "Development of a systematic framework to optimize the production process in shop floor management," *Recent Trends in Industrial and Production Engineering*, Springer, Berlin, Germany, 2021pp. 57–66, Lecture Notes in Mechanical Engineering.

[7] A. Amrani and Y. Ducq, "Lean practices implementation in aerospace based on sector characteristics: methodology and case study," *Production Planning & Control*, vol. 31, no. 16, pp. 1313–1335, 2020.

[8] V. Tripathi, S. Saraswat, G. Gautam, and D. Singh, *Shop Floor Productivity Enhancement Using a Modified Lean Manufacturing Approach*, Springer, Berlin, Germany, 2021.

[9] G. F. Barbosa, J. Carvalho, and E. V. G. Filho, "A proper framework for design of aircraft production system based on lean manufacturing principles focusing to automated processes," *International Journal of Advanced Manufacturing Technology*, vol. 72, no. 9-12, pp. 1257–1273, 2014.

[10] M. Shahin, F. F. Chen, H. Bouzary, and K. Krishnaiyer, "Integration of Lean practices and Industry 4.0 technologies: smart manufacturing for next-generation enterprises," *International Journal of Advanced Manufacturing Technology*, vol. 107, no. 5-6, pp. 2927–2936, 2020.

[11] P. Zheng, H. Wang, Z. Sang et al., "Smart manufacturing systems for Industry 4.0: conceptual framework, scenarios, and future perspectives," *Frontiers of Mechanical Engineering*, vol. 13, no. 2, pp. 137–150, 2018.

[12] J. C. Chen, C.-H. Cheng, P. B. Huang, K.-J. Wang, C.-J. Huang, and T.-C. Ting, "Warehouse management with lean and RFID application: a case study," *International Journal of Advanced Manufacturing Technology*, vol. 69, no. 1-4, pp. 531–542, 2013.

[13] P. V. Ramani and L. K. Lingan, "Developing a lean model to reduce the design process cost of gas insulated switchgear foundation using value stream mapping - a case study," *International Journal of Construction Management*, vol. 22, no. 4, pp. 669–677, 2019.

[14] W. Shou, J. Wang, P. Wu, and X. Wang, "Value adding and non-value adding activities in turnaround maintenance process: classification, validation, and benefits," *Production Planning & Control*, vol. 31, no. 1, pp. 60–77, 2019.

[15] M. Saqlain, M. Piao, Y. Shim, and J. Y. Lee, "Framework of an IoT-based industrial data management for smart manufacturing," *Journal of Sensor and Actuator Networks*, vol. 8, no. 2, pp. 25–2, 2019.

[16] E. V. Gijo, R. Palod, and J. Antony, "Lean Six Sigma approach in an Indian auto ancillary conglomerate: a case study," *Production Planning & Control*, vol. 29, no. 9, pp. 761–772, 2018.

[17] S. Mittal, M. A. Khan, J. K. Purohit, K. Menon, D. Romero, and T. Wuest, "A smart manufacturing adoption framework for SMEs," *International Journal of Production Research*, vol. 58, no. 5, pp. 1555–1573, 2020.

[18] D. Stadnicka and P. Litwin, "Value stream mapping and system dynamics integration for manufacturing line modelling and analysis," *International Journal of Production Economics*, vol. 208, pp. 400–411, 2019.

[19] A. Asif and R. Singh, "Further cost reduction of battery manufacturing," *Batteries*, vol. 3, no. 4, p. 17, 2017.

[20] V. G. Cannas, M. Pero, R. Pozzi, and T. Rossi, "Complexity reduction and kaizen events to balance manual assembly lines: an application in the field," *International Journal of Production Research*, vol. 56, no. 11, pp. 3914–3931, 2018.

[21] B. Das, U. Venkatadri, and P. Pandey, "Applying lean manufacturing system to improving productivity of air-conditioning coil manufacturing," *International Journal of Advanced Manufacturing Technology*, vol. 71, no. 1-4, pp. 307–323, 2014.

[22] C.-F. Chien and C.-C. Chen, "Data-driven framework for tool health monitoring and maintenance strategy for smart manufacturing," *IEEE Transactions on Semiconductor Manufacturing*, vol. 33, no. 4, pp. 644–652, 2020.

[23] P. D. Gaspar, C. M. Fernandez, V. N. G. J. Soares, J. M. L. P. Caldeira, and H. Silva, "Development of technological capabilities through the internet of things (IoT): survey of opportunities and barriers for IoT implementation in Portugal's agro-industry," *Applied Sciences*, vol. 11, no. 8, p. 3454, 2021.

[24] S. Kumar, A. K. Dhingra, and B. Singh, "Process improvement through Lean-Kaizen using value stream map: a case study in India," *International Journal of Advanced Manufacturing Technology*, vol. 96, no. 5-8, pp. 2687–2698, 2018.

[25] J. D. Morales Méndez and R. S. Rodriguez, "Total productive maintenance (TPM) as a tool for improving productivity: a case study of application in the bottleneck of an auto-parts machining line," *International Journal of Advanced Manufacturing Technology*, vol. 92, no. 1-4, pp. 1013–1026, 2017.

[26] A. J. Thomas, M. Francis, R. Fisher, and P. Byard, "Implementing Lean Six Sigma to overcome the production challenges in an aerospace company," *Production Planning & Control*, vol. 27, no. 7–8, pp. 1–13, 2016.

[27] J.-C. Lu and T. Yang, "Implementing lean standard work to solve a low work-in-process buffer problem in a highly automated manufacturing environment," *International Journal of Production Research*, vol. 53, no. 8, pp. 2285–2305, 2015.

[28] D. Torres, C. Pimentel, and S. Duarte, "Shop floor management system in the context of smart manufacturing: a case study," *International Journal of Lean Six Sigma*, vol. 11, no. 5, pp. 823–848, 2020.

[29] S. Tyagi, A. Choudhary, X. Cai, and K. Yang, "Value stream mapping to reduce the lead-time of a product development process," *International Journal of Production Economics*, vol. 160, pp. 202–212, 2015.

[30] P. F. Andrade, V. G. Pereira, and E. G. Del Conte, "Value stream mapping and lean simulation: a case study in automotive company," *International Journal of Advanced Manufacturing Technology*, vol. 85, no. 1-4, pp. 547–555, 2016.

[31] A. Frankó, G. Vida, and P. Varga, "Reliable identification schemes for asset and production tracking in Industry 4.0," *Sensors*, vol. 20, no. 13, pp. 3709–3724, 2020.

[32] V. Gupta, "Application of value stream mapping for lean operations and cycle time reduction: an Indian case study," *Production Planning & Control*, vol. 16, no. 1, pp. 44–59, 2005.

[33] W. Liao and T. Wang, "A novel collaborative optimization model for job shop production-delivery considering time window and carbon emission," *Sustainability*, vol. 11, no. 10, p. 2781, 2019.

[34] S. Vinodh, K. R. Arvind, and M. Somanaathan, "Application of value stream mapping in an Indian camshaft manufacturing organisation," *Journal of Manufacturing Technology Management*, vol. 21, no. 7, pp. 888–900, 2010.

[35] M. J. Beliatis, K. Jensen, L. Ellegaard, A. Aagaard, and M. Presser, "Next generation industrial IoT digitalization for traceability in metal manufacturing industry: a case study of Industry 4.0," *Electronics*, vol. 10, no. 5, p. 628, 2021.

[36] T. Horak, P. Strelec, L. Huraj, P. Tanuska, A. Vaclavova, and M. Kebisek, "The vulnerability of the production line using industrial IoT systems under DDoS attack," *Electronics*, vol. 10, no. 4, p. 381, 2021.

[37] M. Dehghani, Z. Montazeri, Z. Montazeri, H. Givi, J. Guerrero, and G. Dhiman, "Darts game optimizer: a new optimization technique based on darts game," *International Journal of Intelligent Engineering and Systems*, vol. 13, no. 5, pp. 286–294, 2020.

[38] M. Dehghani, Z. Montazeri, Z. Montazeri et al., "MLO: multi leader optimizer," *International Journal of Intelligent Engineering and Systems*, vol. 13, no. 6, pp. 364–373, 2020.

[39] M. Dehghani, Z. Montazeri, O. P. Malik, G. Dhiman, and V. Kumar, "BOSA: binary orientation search algorithm," *International Journal of Innovative Technology and Exploring Engineering*, vol. 9, no. 1, pp. 5306–5310, 2019.

[40] M. Dehghani, Z. Montazeri, G. Dhiman et al., "A spring search algorithm applied to engineering optimization problems," *Applied Sciences*, vol. 10, no. 18, pp. 6173–6221, 2020.

[41] G. Dhiman and V. Kumar, "Spotted hyena optimizer: a novel bio-inspired based metaheuristic technique for engineering applications," *Advances in Engineering Software*, vol. 114, pp. 48–70, 2017.

[42] G. Dhiman and A. Kaur, "STOA: a bio-inspired based optimization algorithm for industrial engineering problems," *Engineering Applications of Artificial Intelligence*, vol. 82, pp. 148–174, 2019.

[43] S. Kaur, L. K. Awasthi, A. L. Sangal, and G. Dhiman, "Tunicate Swarm Algorithm: a new bio-inspired based metaheuristic paradigm for global optimization," *Engineering Applications of Artificial Intelligence*, vol. 90, Article ID 103541, 2020.

[44] G. Dhiman and V. Kumar, "Emperor penguin optimizer: a bio-inspired algorithm for engineering problems," *Knowledge-Based Systems*, vol. 159, pp. 20–50, 2018.

[45] G. Dhiman and V. Kumar, "Seagull optimization algorithm: theory and its applications for large-scale industrial engineering problems," *Knowledge-Based Systems*, vol. 165, pp. 169–196, 2019.

[46] G. Dhiman, D. Oliva, A. Kaur et al., "BEPO: a novel binary emperor penguin optimizer for automatic feature selection," *Knowledge-Based Systems*, vol. 211, Article ID 106560, 2021.

[47] G. Dhiman, *ESA: a hybrid bio-inspired metaheuristic optimization approach for engineering problems*, Springer, no. 1, London, 2021.
[48] G. Dhiman, M. Garg, A. Nagar, V. Kumar, and M. Dehghani, "A novel algorithm for global optimization: rat Swarm Optimizer," *Journal of Ambient Intelligence and Humanized Computing*, vol. 12, no. 8, pp. 8457–8482, 2021.
[49] P. K. Vaishnav, S. Sharma, and P. Sharma, "Analytical review analysis for screening COVID-19 disease," *International Journal of Modern Research*, vol. 1, no. 1, pp. 22–29, 2021.
[50] P. Y. Jang, Y. J. Son, and H. Cho, "Elaboration and validation of AND/OR graph-based non-linear process plans for shop floor control," *International Journal of Production Research*, vol. 41, no. 13, pp. 3019–3043, 2003.
[51] W. Urban, K. Łukaszewicz, and E. Krawczyk-Dembicka, "Application of Industry 4.0 to the product development process in project-type production," *Energies*, vol. 13, no. 21, pp. 5553–21, 2020.
[52] M. Ghobakhloo and N. T. Ching, "Adoption of digital technologies of smart manufacturing in SMEs," *J. Ind. Inf. Integr*, vol. 16, Article ID 100107, 2019.
[53] V. Tripathi, S. Chattopadhyaya, A. Bhadauria et al., "An agile system to enhance productivity through a modified value stream mapping approach in Industry 4.0: a novel approach," *Sustainability*, vol. 13, no. 21, Article ID 11997, 2021.
[54] L.-R. Li, "Lean smart manufacturing in Taiwan-focusing on the bicycle industry," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 5, no. 4, p. 79, 2019.
[55] B. K. Dey, S. Bhuniya, and B. Sarkar, "Involvement of controllable lead time and variable demand for a smart manufacturing system under a supply chain management," *Expert Systems with Applications*, vol. 184, Article ID 115464, 2021.
[56] A. Chiarini and M. Kumar, "Lean six sigma and Industry 4.0 integration for operational excellence: evidence from Italian manufacturing companies," *Production Planning & Control*, vol. 32, no. 13, pp. 1084–1101, 2021.
[57] M. S. Amjad, M. Z. Rafique, and M. A. Khan, "Leveraging optimized and cleaner production through Industry 4.0," *Sustainable Production and Consumption*, vol. 26, pp. 859–871, 2021.
[58] R. Kumar and G. Dhiman, "A comparative study of fuzzy optimization through fuzzy number," *International Journal of Modern Research*, vol. 1, no. 1, pp. 1–14, 2021.
[59] S. M. Sutharsan, M. Mohan Prasad, and S. Vijay, "Productivity enhancement and waste management through lean philosophy in Indian manufacturing industry," *Materials Today Proceedings*, vol. 33, pp. 2981–2985, 2020.
[60] V. Tripathi, S. Saraswat, and G. D. Gautam, "Improvement in shop floor management using ANN coupled with VSM – a case study," *Proceedings of the Institution of Mechanical Engineers - Part C: Journal of Mechanical Engineering Science*, 2021, In press.
[61] I. Chatterjee, "Artificial intelligence and patentability: review and discussions," *International Journal of Modern Research*, vol. 1, no. 1, pp. 15–21, 2021.

Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 2946091, 9 pages
https://doi.org/10.1155/2022/2946091

Research Article

An Optimization Algorithm of Time-Delayed Feedback Control Parameters for Quarter Vehicle Semiactive Suspension System

Yong Guo,[1] **Yuh-Chung Hu**,[2] **and Chuan-Bo Ren**[3]

[1]*School of Mechanical Engineering, Shandong University of Technology, Zibo 255000, China*
[2]*Department of Mechanical and Electromechanical Engineering, National Ilan University, Shenlung Road, Yilan 26047, Taiwan*
[3]*School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo 255000, China*

Correspondence should be addressed to Chuan-Bo Ren; chuanbor@sdut.edu.cn

Received 6 August 2021; Revised 29 August 2021; Accepted 1 September 2021; Published 30 April 2022

Academic Editor: Kuei-Hu Chang

Time-delayed feedback control is commonly used on the vehicle semiactive suspension system to improve ride comfort and safety. However, its performance on the suppression of road random excitation is less significant than that on the suppression of simple harmonic excitation. Therefore, this paper proposes a strategy of time-delayed feedback control with the vertical displacement of wheel and the method of optimizing its parameters based on equivalent harmonic excitation. The optimal parameters of the time-delayed feedback control are obtained in this way for the vehicle semiactive suspension system in its effective frequency band. The results of numerical simulation verify that the time-delayed feedback control with vertical wheel displacement and its parameter optimization based on equivalent harmonic excitation can significantly improve the ride comfort and stability. Its performance is much better than that of the passive suspension system.

1. Introduction

Modern automobile is developing in the direction of safety, comfort, energy saving, environmental protection, and intelligence. People's pursuit of automobile ride comfort and overall quality is also increasing. As one of the important components of modern automobile, the main function of vehicle suspension system is to alleviate the impact and vibration caused by road roughness and improve the ride comfort of vehicles, as well as maintaining the adhesion between the tire and the ground, so as to improve the handling stability of the vehicle. In general, the conventional passive suspension system consists of elastic components and damper with fixed parameters. Although it has the advantages of simple structure and low cost, its structural parameters cannot be adjusted automatically in complex and changeable external conditions and different driving states of vehicles, and the passive suspension system can achieve the optimal performance only under a specific combination of speed and road conditions. In order to improve the ride performance of vehicles, the present research on active and semiactive suspension systems, which can improve the driving characteristics according to the driving states of the vehicle and road conditions, focuses mainly on the control algorithm, stability characteristics, and test methods [1–4]. However, due to a series of factors, such as signal acquisition, transmission, controller calculation, and actuation delay, several time delay factors inevitably arise. The existence of time delay reduces the performance of the suspension system. It may even lead to the instability of the suspension system, thus affecting the safety of vehicle driving [5, 6]. In the past, time delay was usually regarded as an unfavorable factor leading to the instability of the active and semiactive suspension systems of vehicles. Therefore, in order to improve the control accuracy and stability of the suspension system of vehicles, most researchers reduce or eliminate the adverse effects of time delay by combining the time delay compensation technology with the modern control technology [7–9]. However, from the in-depth study of time delay, it is found that time delay can also change the effective frequency range of the saturation control [10–12]. The vibration control effect of the main system can be improved effectively by adjusting the time delay as a feedback control parameter. Olgac and Holm-Hansen [13] introduced the time-delayed feedback control in the dynamic vibration absorber for the first time and proposed the concept of delayed resonator. Their results showed that if appropriate delay feedback control parameters (feedback gain and feedback delay) are chosen, the delayed resonator can completely absorb the vibration of the main system under harmonic excitation; that is, the vibration of the main system will disappear. Liu and Sun et al. [14] constructed a vehicle suspension model of two-degree-of-freedom based on the time-delayed feedback control of the vertical acceleration of the body and optimized the time-delayed feedback control parameters of the vehicle suspension system under different harmonic excitation frequencies of road. The optimization results showed that, in comparison to the passive suspension system, the vibration isolation effect of the vehicle suspension system under the optimal time-delayed feedback control was effectively improved. The acceleration amplitude of the vehicle body could also be reduced by at least 19.60%. Yan and Fang [15] studied a vehicle suspension system of two-degree-of-freedom based on time-delayed feedback control of the vertical velocity of the body. They used a genetic algorithm to optimize the structural parameters and control gain of suspension. The optimization results showed that, under a certain inherent time delay, the acceleration amplitude in the optimized sprung mass was reduced by 22.7%. Qu and Ren et al. [16] constructed a four-degree-of-freedom vehicle suspension model based on dual-delayed feedback control, and the particle swarm optimization algorithm was adopted to study the optimization of time-delayed feedback control parameters of vehicle suspension system under road random excitation. The results show that, compared with the passive suspension system, the acceleration amplitude of the vehicle body is 15.1% lower than that before optimization. Huang and Zhao [17] introduced a time-delayed feedback control into the mode of a two-degree-of-freedom semiactive suspension system to suppress the lateral vibration of the high-speed train, and the results show that, compared with the passive suspension system, the amplitude of the body's lateral vibration could be suppressed about 50% when the suitable values of damping coefficient and time delay are chosen.

In view of this, from the perspective of the utilization of time delay, it is rare to introduce time delay into the field of vehicle engineering applications, and the key to improving the performance of the vehicle suspension control system is to obtain the optimal time-delayed feedback control parameters (feedback gain and feedback delay). However, in the current research of quarter vehicle semiactive suspension system based on time-delayed feedback control, there are still the following main problems:

(1) Generally, only the damping effect of the vertical acceleration of the vehicle body near the resonance frequency point under the optimal time-delayed feedback control is considered. But the output response of other suspension performance evaluation indexes such as suspension dynamic stroke and tire dynamic displacement is not accurately understood. However, these three kinds of performance evaluation indicators are usually contradictory; that is to say, if we want to get better riding comfort, it will usually lead to the reduction of driving stability. Similarly, if we improve the driving stability, it will usually lead to the reduction of riding comfort. Therefore, only taking the output response of the vertical acceleration of the vehicle body as the evaluation index of the vibration reduction effect of the vehicle suspension system, there are some limitations in the evaluation of the comprehensive performance of the vehicle semiactive suspension system based on the time-delayed feedback control.

(2) Generally, the road conditions of vehicles are dominated by simple road harmonic excitation. The vibration reduction effect of vehicle semiactive suspension system based on time-delayed feedback control under road harmonic excitation is relatively good, but the vibration reduction effect under road random excitation is usually not as significant as that under road harmonic excitation. Therefore, in order to solve the problem of a complex time-varying excitation, such as external multifrequency, the general method for solving the appropriate time-delayed feedback control parameters still needs to be explored further.

In view of the above problems, this paper takes the two-degree-of-freedom quarter car model based on time-delayed feedback control as the basic research object; a strategy of time-delayed feedback control with vertical displacement of the wheel and an optimization method of time-delayed feedback control parameters based on "equivalent harmonic excitation" are proposed for vehicle semiactive suspension system with time-delayed feedback control. In the final case analysis, the optimal values of time-delayed feedback control parameters of the vehicle suspension system in the effective frequency band are obtained through particle swarm optimization algorithm. The numerical simulation results of time-domain response show that, compared with the passive suspension system, the semiactive suspension system based on time-delayed feedback control with wheel displacement can significantly improve the ride comfort and stability of the vehicle under the optimal time-delayed feedback control, where the comprehensive performance of the suspension is improved.

2. Mechanical Model of the Time-Delayed Feedback Control for Vehicle Suspension System

In this paper, taking magnetorheological damper as active control actuator, a time-delayed feedback control based on wheel displacement is introduced into vehicle passive suspension system. The mechanical model of vehicle semiactive suspension system based on time-delayed feedback control of wheel displacement is established, and the model is shown in Figure 1.

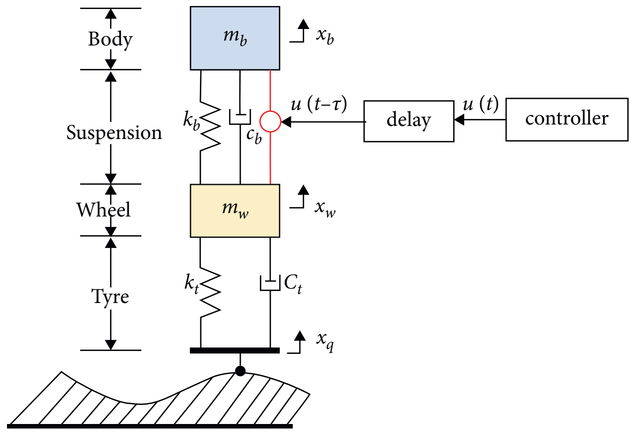


FIGURE 1: Mechanical model for controlling time-delayed vibration reduction in vehicle suspension system.

TABLE 1: Model parameters of vehicle suspension system.

Parameter	Value	Parameter	Value
m_b (kg)	136.05	mw (kg)	24.29
cb ($\mathrm{N{\bullet}s{\bullet}m^{-1}}$)	153	ct ($\mathrm{N{\bullet}s{\bullet}m^{-1}}$)	15
kb ($\mathrm{N{\bullet}m^{-1}}$)	10200	kt ($\mathrm{N{\bullet}m^{-1}}$)	9800

The design parameters of vehicle semiactive suspension system are shown in Table 1 where mb is the quarter vehicle body mass (sprung mass), m_w is the unsprung mass, c_b is the damper coefficient of semiactive suspension, k_b is the spring stiffness of semiactive suspension, c_t is the damper coefficient of tire, k_t is the equivalent stiffness of tire, and $u(t\text{-}\tau)$ is the time-delayed feedback control force between sprung mass and unsprung mass. In addition, x_b is the vertical displacement of sprung mass, x_w is the vertical displacement of unsprung mass, and x_q is the vertical displacement of road roughness excitation.

According to the mechanical model for controlling the time-delayed vibration reduction as shown in Figure 1, the origin of the coordinate system is selected at the respective equilibrium positions of the wheel and the body. The equation of dynamic motion of the vehicle suspension system is formulated as follows:

$$\begin{cases} m_b\ddot{x}_b + c_b\dot{x}_b - c_b\dot{x}_w + k_bx_b - k_bx_w - u(t-\tau) = 0, \\ m_w\ddot{x}_w - c_b\dot{x}_b + (c_b + c_t)\dot{x}_w - k_bx_b + (k_b + k_t)x_w \\ \quad + u(t-\tau) = c_t\dot{x}_q + k_tx_q. \end{cases} \tag{1}$$

In practical applications, in view of the flexibility of sensor selection, the type of time-delayed feedback (time-delayed feedback control signal) mainly includes the single time-delayed feedback type of displacement [18], velocity [19], acceleration [20], and the combination of them [21]. The time-domain function based on the time-delayed feedback with vertical displacement of the vehicle body can be expressed as follows:

$$u(t-\tau) = g_w \cdot x_w(t-\tau_w), \tag{2}$$

where gw represents the coefficient of the time-delayed feedback gain and τw is the time delay (inherent and active time delay). The time delay from signal acquisition to input and the time delay of the MR damper response are the inherent feedback delay of the system, while the active time delay is an artificial time delay in the control loop of the suspension, which can be regarded as an adjustable parameter for improving the suspension performance of the control system. When $u(t\text{-}\tau)$ disappears, the semiactive suspension system based on the time-delayed vibration reduction control will degenerate into a vibration reduction system of the passive suspension.

Equations (1) to (2) are simplified and identified by matrix equation, and the result can be written as

$$\mathrm{M}\ddot{\mathrm{X}} + \mathrm{C}\dot{\mathrm{X}} + (\mathrm{K} + \mathrm{A})\mathrm{X} = \mathrm{K_t}\mathrm{X_q} + \mathrm{C_t}\dot{\mathrm{X}}_\mathrm{q}. \tag{3}$$

Let the root of the characteristic equation of (3) be s; after Laplace transformation, (4) can be obtained as

$$\left(\mathrm{M}s^2 + \mathrm{C}s + \mathrm{K} + A(s)\right)\mathrm{X}(s) = [\mathrm{K_t} + \mathrm{C_t}s]\mathrm{X_q}(s), \tag{4}$$

where

$$\begin{gathered} \mathrm{M} = \begin{bmatrix} m_b & 0 \\ 0 & m_w \end{bmatrix}, \\ \mathrm{C} = \begin{bmatrix} c_b & -c_b \\ -c_b & c_b + c_t \end{bmatrix}, \\ \mathrm{K} = \begin{bmatrix} k_b & -k_b \\ -k_b & k_b + k_t \end{bmatrix}, \\ \mathrm{A}(s) = \begin{bmatrix} 0 & -g_w \cdot e^{-s\tau_w} \\ 0 & g_w \cdot e^{-s\tau_w} \end{bmatrix}. \end{gathered} \tag{5}$$

And

$$\begin{gathered} \mathrm{K_t} = \begin{bmatrix} 0 & 0 \\ 0 & k_t \end{bmatrix}, \\ \mathrm{C_t} = \begin{bmatrix} 0 & 0 \\ 0 & c_t \end{bmatrix}, \\ \mathrm{X}(s) = \begin{Bmatrix} X_b(s) \\ X_w(s) \end{Bmatrix}, \\ \mathrm{X_q}(s) = \begin{Bmatrix} 0 \\ X_q(s) \end{Bmatrix}. \end{gathered} \tag{6}$$

3. Stability Analysis of Vehicle Suspension System with Time-Delayed Feedback Control

The feedback gain and feedback delay will affect the stability of the system after the introduction of time-delayed feedback control. Therefore, in order to ensure that the semiactive suspension system can work in a stable state, it is necessary to analyze its stability. According to (4), let $\mathrm{M}s^2 + \mathrm{C}s + K + \mathrm{A}(s) = G(s)$, and the expression of $G(s)$ can be derived by the following:

$$\mathrm{G}(s)=\begin{bmatrix} m_b s^2+c_b s+k_b & -c_b s-k_b-g_w\cdot e^{-s\tau_w} \\ -c_b s-k_b & m_w s^2+(c_b+c_t)s+k_t+k_b+g_w\cdot e^{-s\tau_w} \end{bmatrix}. \tag{7}$$

According to the nonzero solution condition of the equation, the characteristic equation of vehicle suspension system based on time-delayed feedback control with wheel displacement can be obtained as follows:

$$P(s)+Q(s)e^{-\tau_w s}=0, \tag{8}$$

where

$$\begin{aligned} P(s) &= m_b m_w s^4+(c_b m_b+c_t m_b+c_b m_w)s^3 \\ &\quad +(k_b m_b+k_t m_b+k_b m_w+c_b c_t)s^2 \\ &\quad +(c_b k_t+c_t k_b)s+k_b k_t, \\ Q(s) &= -g m_b s^2. \end{aligned} \tag{9}$$

According to the Routh–Hurwitz criterion, the necessary and sufficient condition for system stability is that all the characteristic roots of (8) have negative real parts, and the critical condition for system instability is that the characteristic roots of (8) are only pure virtual roots $s=\mathrm{i}\omega c$. Therefore, substituting $s=\mathrm{i}\omega c$ into (8) and using Euler's formula to separate the real and imaginary parts of the equation, the expressions of $\sin(\omega_c\tau_w)$ and $\cos(\omega_c\tau_w)$ can be obtained. According to $\sin^2(\omega_c\tau_w)+\cos^2(\omega_c\tau_w)=1$, the available high order polynomial (10) is as follows:

$$a_8\omega_c^8++a_6\omega_c^6+a_4\omega_c^4+a_2\omega_c^2+a_0=0. \tag{10}$$

In equation (10), a_8, a_6, a_4, a_2, and a_0 are the polynomial coefficients related to the suspension.

System parameters and their expression can be derived by the following:

$$\begin{aligned} a_8 &= m_b^2+m_w^2, \\ a_6 &= \left(c_b^2+c_t^2+2c_b c_t\right)m_b^2+\left(c_b^2-2k_b m_b\right)m_w^2 \\ &\quad -2(k_b+k_t)m_b^2 m_w+2c_b^2 m_b m_w, \\ a_4 &= \left(c_b^2c_t^2+2c_b^2k_t-2c_t^2k_b-2c_t^2k_b\right)m_b \\ &\quad +\left(k_b^2+k_t^2+2k_b k_t\right)m_b^2+\left(2k_b^2+4k_b k_t\right)m_b m_w \\ &\quad +k_b^2m_w^2-2c_b^2k_t m_w+\left(-g^2+k_t^2\right)m_b^2, \\ a_2 &= c_b^2k_t^2+c_t^2k_b^2-\left(2k_t^2k_b+2k_b^2k_t\right)m_b-2k_b^2k_t m_w, \\ a_0 &= k_b^2k_t^2. \end{aligned} \tag{11}$$

It can be seen from (10) that when the hysteresis feedback gain gw is a certain value, the coefficient a_λ ($\lambda=0, 2, 4, 6, 8$) determines the value of the root of the equation. The number of positive real roots of (10) is defined as N. If $N=0$, the stability of the system does not switch. That is to say, the stability of the system does not change when τ is taken as any positive real number. If $N\neq 0$, the root number of the system is N, and for each ω^{cm} ($m=1, 2, \ldots, N$), there are infinitely critical delay values τ^{cn} ($n=1, 2, \ldots, \infty$) corresponding with it. When τ_w crosses from $\tau_{wcn}-\varepsilon$ to $\tau_{wcn}+\varepsilon$ ($0<\varepsilon<1$), the changing trend of the real part of the characteristic root of the equation can be determined by the following equation:

$$RT=\operatorname{sgn}\left[\operatorname{Re}\left(\frac{\partial s}{\partial\tau}\right)|s=\omega_{cm}i, i=\sqrt{-1}\right]. \tag{12}$$

If $\mathrm{RT}=1$, it means that the number of unstable characteristic roots of the characteristic (12) increases by 2, when τw crosses the critical value from left to right. If $\mathrm{RT}=-1$, it means that the number of unstable characteristic roots of the characteristic (12) decreases by 2 [22, 23]. Different feedback gains g are selected in turn, and the above analysis process is repeated; the stability partition diagram on the (g, τ) plane can be obtained as shown in Figure 2. It can be seen from the stability partition in Figure 2 that the system is stable when (g, τ) is located in the shaded region, and the system is unstable when (g, τ) is located in the blank region.

4. Optimization of Time-Delayed Feedback Control Parameters in Vehicle Semiactive Suspension System

4.1. Construction of Optimization Objective Function. According to (4), the transfer function matrix H(s) of vehicle suspension system with time-delayed feedback control can be obtained as

$$\mathrm{H}(s)=\frac{\mathrm{X}(s)}{\mathrm{X_q}(s)}=\frac{\mathrm{K_t}+\mathrm{C_t}s}{\mathrm{M}s^2+\mathrm{C}s+\mathrm{K}+A(s)}. \tag{13}$$

With the frequency-domain analysis method, $\mathrm{i}\omega$ is used to replace the operator s in (13), and the frequency response transfer function matrix can be obtained as

$$\mathrm{H}(i\omega)=\frac{\mathrm{X}(i\omega)}{\mathrm{X_q}(i\omega)}=\frac{\mathrm{K_t}+\mathrm{C_t}(i\omega)}{-\omega^2\mathrm{M}+i\omega\mathrm{C}+\mathrm{K}+A(i\omega)}. \tag{14}$$

For the quarter car model, the vertical acceleration of the vehicle body is an important characteristic to measure the vibration effect of the vehicle suspension system. The minimum dimensionless amplitude frequency characteristic function of vehicle body vertical acceleration in the effective frequency band is taken as the objective function [24, 25], and the objective function $J(g_w, \tau_w)$ is established, as shown in (15)

$$\min J(g_w,\tau_w)=\frac{|\mathrm{H}(i\omega)|_{\ddot{x}_b\sim x_q}-\min|\mathrm{H}(i\omega)|_{\ddot{x}_b\sim x_q}}{\max|\mathrm{H}(i\omega)|_{\ddot{x}_b\sim x_q}-\min|\mathrm{H}(i\omega)|_{\ddot{x}_b\sim x_q}},$$

$$s.t.\begin{cases} \underline{g}_w\leq g_w\leq\overline{g}_w, \\ \underline{\tau}_w\leq\tau_w\leq\overline{\tau}_w. \end{cases} \tag{15}$$

Obviously, the smaller the value of the objective function, the better the ride comfort of the vehicle. However, the selection of time-delayed feedback control parameters should not only meet the requirements of vehicle ride

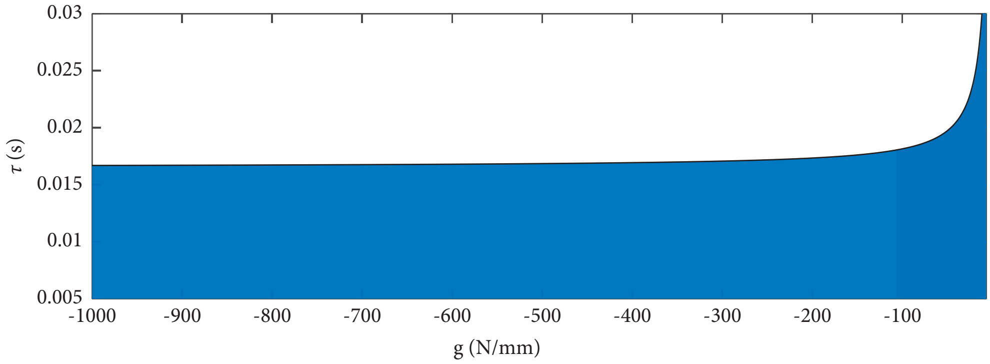


FIGURE 2: Division of suspension full time delay stability region under wheel displacement feedback control.

comfort to the greatest extent but also consider other performance evaluation indexes of suspension system, such as suspension dynamic travel and tire dynamic displacement output response, so as to comprehensively improve the comprehensive performance of suspension system. Therefore, according to the constraint range of the feedback control parameters, which can satisfy the full delayed stability of the suspension system shown in Figure 2, the numerical search range of the proposed feedback gain is $-k_b \leq g_w \leq k_b$; if the numerical search range of feedback delay τ_w is set as $0.0001 \leq \tau_w \leq 0.01$, the constraint condition of the time-delayed feedback control parameters is expressed as (16)

$$\begin{aligned} -k_b \leq g_w \leq k_b, \\ 0.0001 \leq \tau_w \leq 0.01. \end{aligned} \tag{16}$$

4.2. Time-Domain Model of Road Roughness. Establishing a reasonable time-domain model of road roughness is one of the most important issues in the follow-up study of dynamic characteristics of vehicle suspension system under random road excitation. At present, the main methods to simulate the road random excitation model at home and abroad are the harmonic superposition method, Fourier inverse change method, filtered white noise method, and time series model method. In view of the time-delayed vibration reduction effect of the vehicle body under the condition of road harmonic excitation which is remarkable, the time-domain model of random road excitation that is based on the harmonic superposition method is selected [26, 27]. The time-domain model can be expressed as

$$x_q(t) = \sum_{1}^{k} \sqrt{2G_q\left(f_{mid-j}\right) \cdot \Delta f_j} \cdot \sin\left(2\pi f_{mid-j} t + \theta_j\right), \quad (j = 1, 2, 3, \ldots k). \tag{17}$$

Due to the randomness of road excitation in the process of vehicle driving, the structural parameters that usually need to be selected in the establishment of a concrete pavement excitation model mainly include pavement grade roughness coefficient Gq ($f_{mid\text{-}j}$), effective time and frequency interval (f_1; f_2), and the number of parts k to separate them. The selection range of time frequency should include the main natural frequency of vehicle vibration. The division of time and frequency interval should take into account the operation efficiency and the fitting accuracy of the given road spectrum.

4.3. Optimization of Time-Delayed Feedback Control Parameters in Effective Frequency Band. In this paper, it is assumed that the vehicle travels at a speed of v = 60 km/h on the C-class road surface, so the road roughness coefficient is $Gq(f) = 256 \times 10^{-6} m^3$. Generally, the frequency range of vehicle vibration caused by road roughness is about 0.25 Hz–15 Hz. When it is lower than 15 Hz, the body motion can be assumed to be a simple rigid body motion. When it is higher than 15 Hz, the dynamic modeling requires an accurate description of the vehicle structure. In this paper, the lower limit and the upper limit of the time frequency of the road acting on the tire excitation are taken as $f_1 = 0.25$ Hz and $f_2 = 15$ Hz, respectively.

According to the product of time frequency and space frequency $f = v \cdot n$, the lower limit of effective spatial frequency $n_1 = 0.015\ m^{-1}$ and the upper limit of effective spatial frequency $n_2 = 0.9\ m^{-1}$ of road roughness power spectral density are obtained. In order to avoid frequency aliasing, the sampling interval is set as Δl, Δl ≤ 0.5·v·f2–1, which can be obtained from the sampling theorem. If the number of sampling points is N, the length of simulated road roughness shall be $L = N \cdot \Delta l$, and the resolution of sampling spatial frequency shall be Δn = L–1. In order to ensure the validity of the lower limit frequency n1, then $\Delta n \leq n1$, so $L \geq n_{1-1} = v \cdot f_{1-1}$. According to the constraint of sampling interval Δl, Δl can be selected as 0.015 m^{-1}. The effective spatial frequency interval (n1, n2) of road roughness power spectral density is divided into $k = 59$ small areas in turn. The center frequency of each space cell is $n_{mid-j} = 0.015 \cdot j + 0.0075$ for j = (1,2,3, . . ., 59). Then the interval length of time frequency is Δfj = 0.25, which leads to $f_{mid-j} = 0.25 \cdot j + 0.125$ for j = (1,2, . . ., 59).

As the time-domain model of random road roughness shown in equation (17) and the constraint conditions of time-delayed feedback control parameters shown in (16) are referenced, the particle swarm optimization algorithm with

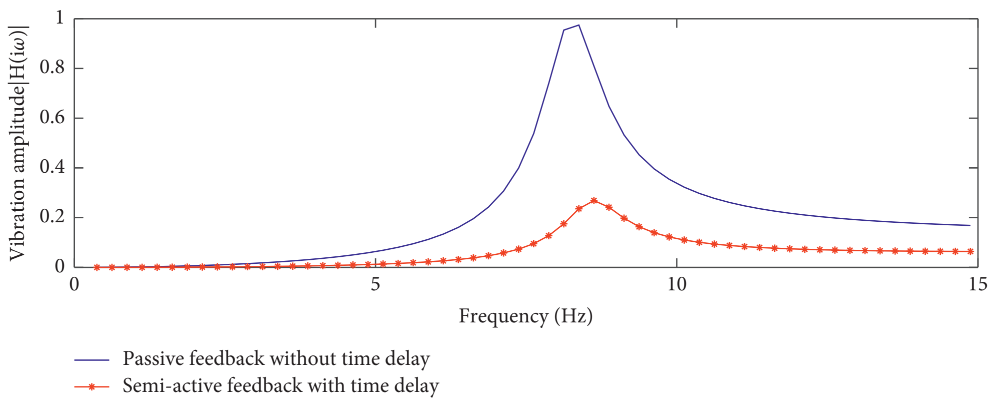


FIGURE 3: Amplitude frequency characteristic curve of the vertical acceleration of the vehicle body.

$J(g_w, \tau_w)$ as fitness function is constructed by using equivalent harmonic excitation method. That is, in the effective frequency band (f_1; f_2), a series of discrete frequency points are selected at equal intervals and divided into multiple cells. By taking the harmonic excitation at the center frequency of each cell as the optimization strategy of the equivalent harmonic excitation of the whole cell, the particle swarm optimization algorithm with the vertical acceleration of the vehicle body as the optimization objective function is constructed so as to obtain the optimal value of the delay feedback control parameters in the effective frequency band.

In view of the characteristics that the vibration reduction effect of vehicle semiactive suspension system under road random excitation is usually not as significant as that under road harmonic excitation, the reason is that the corresponding optimization objective function is mostly constructed by Fourier transform and frequency-domain transfer function, but the time-varying state of external excitation is not considered in the optimization process of time-delayed feedback control parameters, and the time-delayed feedback control parameters obtained by optimization solution are only local optimal values. In this paper, in order to avoid the optimization result of time-delayed feedback control parameters as local optimal value as far as possible, according to the expression of amplitude frequency characteristic function based on vertical acceleration of vehicle body shown in (18),

$$\left|H\left(i\omega_{mid-j}\right)\right|_{\ddot{x}_b\sim x_q} = \omega^2\left|\frac{X_b\left(i\omega_{mid-j}\right)}{X_q\left(i\omega_{mid-j}\right)}\right|, \tag{18}$$

where the amplitude of the road excitation at the center frequency of each interval (i.e., $|x_q\,(f_{mid-j})|$) is assumed to be the peak value of the road excitation in the effective frequency band (f_1; f_2), which can effectively reduce the amplitude of vertical acceleration based on the center frequency of each interval in the whole frequency band.

Finally, the particle swarm optimization algorithm with the vertical acceleration of the vehicle body as the optimization objective function is constructed to obtain the optimal value of the time-delayed feedback control parameters in the effective frequency band. On the basis of this optimization strategy, 200 particles are randomly selected for iterative optimization, and the optimal value of the time-delayed feedback control parameters of the vehicle semiactive suspension system in the effective frequency band is obtained, that is, (gwop, τwop) = (−8356.7 N/m, 0.0056 s), and the amplitude frequency characteristic curve of the vertical acceleration of the vehicle body in the effective frequency band is obtained as shown in Figure 3.

4.4. Results and Discussion. According to the frequency-domain simulation results of the vertical acceleration of the vehicle body shown in Figure 3, it can be seen that, compared with the vertical acceleration amplitude of the passive control suspension system, at the frequency $f = 8.3750$ Hz, the corresponding amplitude of the vehicle body vertical acceleration decreases from 0.9746 of the passive control to 0.2357 of the time-delayed feedback control, and at the frequency $f = 8.6250$ Hz, the corresponding amplitude of the vehicle body vertical acceleration decreases from 0.8100 of the passive control to 0.2687 of the time-delayed feedback control, while the peak values of passive suspension system and delayed feedback control suspension system in the whole frequency band are 0.9746 and 0.2687, respectively. Therefore, the amplitude frequency characteristics of the vertical acceleration of the vehicle body are effectively improved under the optimal time-delayed feedback control.

5. Time-Domain Simulation Analysis of Vehicle Semiactive Suspension System

In order to verify the correctness of the optimization results of time-delayed feedback control parameters, the time-domain response of various performance evaluation indexes of vehicle semiactive suspension system based on time-delayed feedback control under road excitation needs to be numerically simulated, analyzed, and verified.

5.1. Time-Domain Simulation Analysis under Harmonic Road Excitation. Based on the center frequency of each section in the effective frequency band, $f_{mid-1} = 0.375$ Hz is selected. Then the road excitation is simple harmonic excitation; that is, $x_q(t) = 0.0123\ \sin\ (2\pi f_{mid-1} t + \theta_{-1})$. According to the

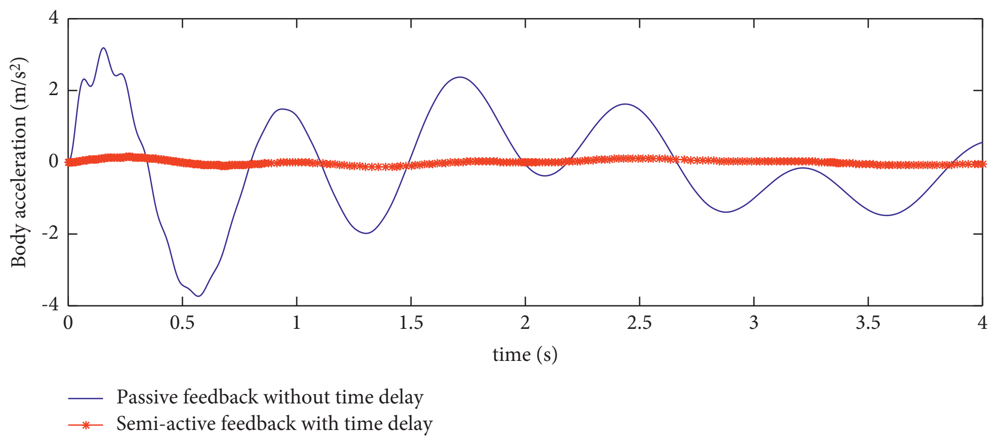


FIGURE 4: Time-domain response characteristic curve of vehicle body vertical acceleration.

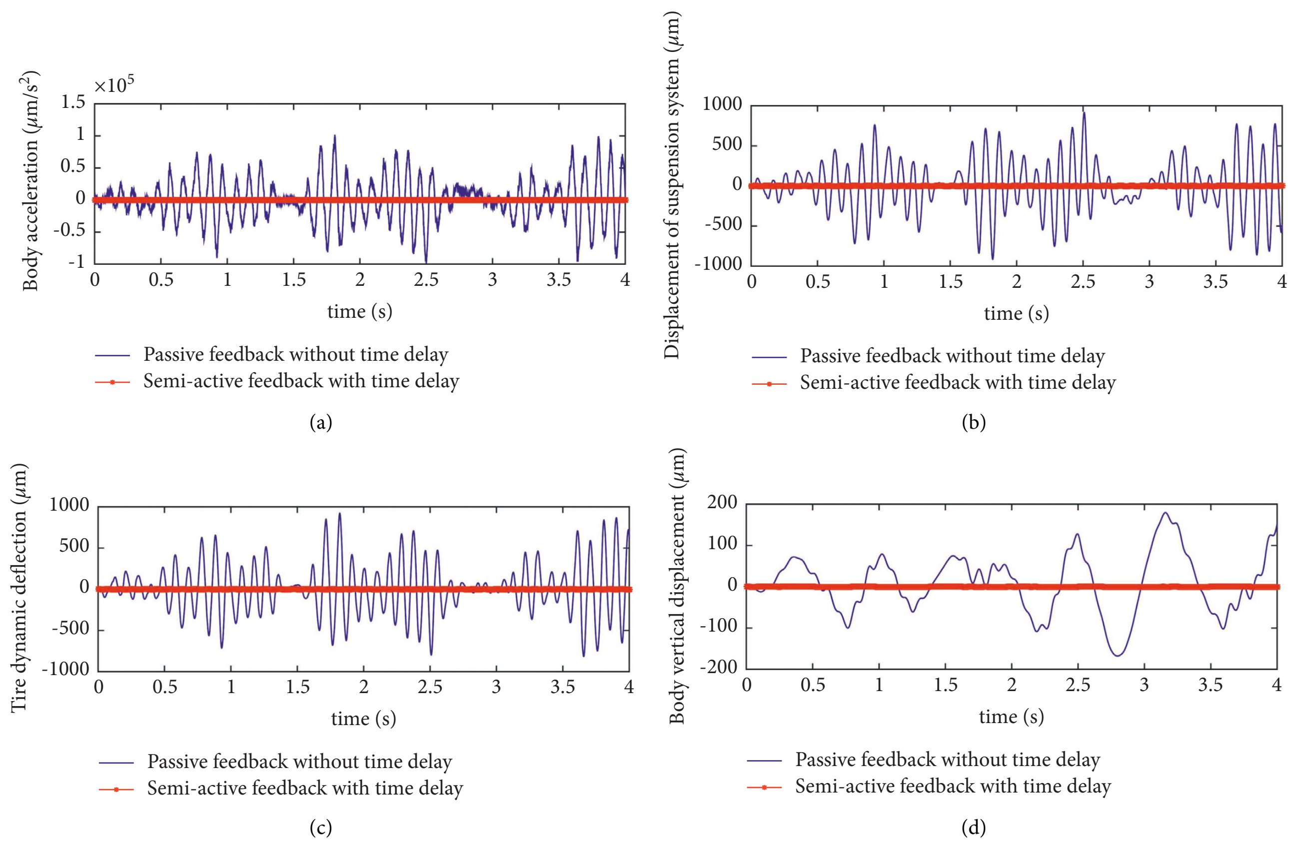


FIGURE 5: Time-domain simulation results of various performance evaluation indexes of vehicle suspension system. (a) Body vertical acceleration. (b) Suspension dynamic stroke. (c)Tire dynamic displacement. (d) Vertical displacement of vehicle body.

optimal value of time-delayed feedback control parameters (gwop; τwop), through numerical simulation analysis, the time-domain response of vehicle body vertical acceleration based on time-delayed feedback control of wheel displacement can be obtained, as shown in Figure 4.

5.2. Results and Discussion under Harmonic Road Excitation. Time-domain simulation results show that, compared with the passive control, the time-delayed feedback control significantly reduces the amplitude of vertical acceleration of vehicle body under harmonic excitation, and the corresponding root mean square value is reduced from $1.5730\,\mathrm{m{\bullet}s^{-2}}$ in passive control to $0.0699\,\mathrm{m{\bullet}s^{-2}}$ in time-delayed feedback control. So the optimization efficiency is 95.5587%.

5.3. Time-Domain Simulation Analysis under Random Road Excitation. With the C-level road roughness as the

Table 2: Comparison of RMS of various performance evaluation indexes of passive suspension and time-delayed feedback control suspension system.

Performance evaluation index	Passive suspension	Time-delayed feedback suspension	Difference (%)
Vertical acceleration (μm/s2)	14238	8.6600	99.9392
Suspension dynamic travel (μm)	173.46	2.3013	98.6733
Wheel displacement (μm)	154.34	2.1973	98.5764
Vertical displacement (μm)	87.576	0.6952	99.2062

excitation and the help of the Matlab platform, according to the optimal value of the time-delayed feedback control parameters, the time-domain response simulation results of the vehicle semiactive suspension system and vehicle passive control suspension system are compared and analyzed. The simulation results of vehicle vertical acceleration, suspension dynamic travel, and tire dynamic displacement are items that are compared and analyzed. The time-domain simulation results are shown in Figure 5.

5.4. Results and Discussion under Random Road Excitation. According to the comparison of the root mean square values of various performance evaluation indexes of vehicle suspension system under random road excitation shown in Table 2, the following results can be drawn:

(1) Compared with the passive control, the time-delayed feedback control significantly reduces the amplitude of vertical acceleration, and the RMS value of vertical acceleration decreases from 14238 μm/s2 of passive control to 8.6600 μm/s2 of time-delayed feedback control. Therefore, the optimization efficiency is 99.9392%.

(2) Compared with the passive control, the time-delayed feedback control significantly reduces the amplitude of suspension dynamic travel, and the RMS value of vertical acceleration decreases from 173.46 μm of passive control to 2.3013 μm of time-delayed feedback control. Therefore, the optimization efficiency is 98.6733%.

(3) Compared with the passive control, the time-delayed feedback control significantly reduces the amplitude of tire dynamic displacement, and the RMS value of vertical acceleration decreases from 154.34 μm of passive control to 2.1973 μm of time-delayed feedback control. Therefore, the optimization efficiency is 98.5764%.

(4) Compared with the passive control, the time-delayed feedback control significantly reduces the amplitude of vertical displacement, and the RMS value of vertical acceleration decreases from 87.576 μm of passive control to 0.6952 μm of time-delayed feedback control. Therefore, the optimization efficiency is 99.2062%.

6. Conclusions

In this paper, the mechanical model of vehicle semiactive suspension system based on time-delayed feedback control of wheel displacement is studied. In the example analysis, the optimization strategy based on "equivalent harmonic excitation" and particle swarm optimization algorithm are adopted to optimize and solve the time-delayed feedback control parameters involved in the model in this paper. Then, through numerical simulation analysis and verification, the following conclusions are drawn:

(1) Compared with the passive suspension system, the vehicle semiactive suspension system based on time-delayed feedback control with wheel displacement under the optimal time-delayed feedback control can effectively broaden the vibration absorption bandwidth of the vehicle suspension system.

(2) Compared with the passive suspension system, the vehicle semiactive suspension system based on time-delayed feedback control with wheel displacement can significantly improve the ride comfort and stability of the vehicle under the optimal time-delayed feedback control, which means that the comprehensive performance of the suspension is improved.

(3) The effectiveness of the time-delayed feedback control strategy based on wheel displacement and the parameter optimization strategy based on "equivalent harmonic excitation" is verified, which provides a theoretical reference for the optimal design of time-delayed feedback control parameters of the vehicle suspension system.

Data Availability

The data used to support the findings of this study have not been made available so as to ensure the privacy and anonymity of the people involved.

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this paper.

Acknowledgments

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this paper. This study was supported by the National Natural Science Foundation of China (Grant no. 51275280).

References

[1] R. C. Wang, L. Chen, X. L. Zhang, and X. H. Zhu, "Design and test of semi-active air suspension system of vehicle," *Transactions of the Chinese Society for Agricultural Machinery*, vol. 43, no. 4, pp. 6–9, 2012.

[2] K. H. Guo, W. H. Yu, X. J. Zhang, F. W. Ma, and F. Q. Zhao, "Semi-active suspension adaptive control strategy," *Journal of Hunan University*, vol. 40, no. 2, pp. 39–44, 2013.

[3] I. Mihai and F. Andronic, "Behavior of a semi-active suspension system versus a passive suspension system on an uneven road surface," *Mechanics*, vol. 20, no. 1, pp. 64–69, 2014.

[4] C. H. Zhao, S. A. Chen, and J. H. Wang, "Influences of stiffness and damping parameters on control of active suspension based on LQG," *Transactions of the Chinese Society for Agricultural Machinery*, vol. 46, no. 12, pp. 30–308, 2015.

[5] L. Chen, R. C. Wang, H. B. Jiang, L. K. Zhou, and S. H. Wang, "Time delay on semi-active suspension and control system," *Chinese Journal of Mechanical Engineering*, vol. 42, no. 1, pp. 130–133, 2006.

[6] G. Wang, C. Z. Chen, and S. B. Yu, "Finite frequency multi-objective control of vehicle active suspension with road preview information," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 46, no. 12, pp. 294–300, 2015.

[7] G. Song and C. C. Xu, "Stochastic optimal preview control of active vehicle suspension with time-delay consideration," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 44, no. 6, pp. 1–7, 2013.

[8] G. Yan, M. X. Fang, Q. F. Dong, and R. J. Ji, "Time-delayed feedback control of vehicle suspension system based on state Transformation," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 34, no. 10, pp. 54–61, 2018.

[9] W. Q. Fu, H. Pang, and K. Liu, "Modeling and Stability analysis of semi-active suspension with sky-hook damper coefficients considering time delay," *Mech Sci Technol Aerosp Eng*, vol. 36, no. 2, pp. 213–218, 2017.

[10] J. Xu, K. W. Chung, and Y. Y. Zhao, "Delayed saturation controller for vibration suppression in a stainless-steel beam," *Nonlinear Dynamics*, vol. 62, no. 1-2, pp. 177–193, 2010.

[11] Y.-Y. Zhao and J. Xu, "Performance analysis of passive dynamic vibration absorber and semi-active dynamic vibration absorber with delayed feedback," *International Journal of Nonlinear Sciences and Numerical Stimulation*, vol. 8, no. 4, pp. 607–614, 2007.

[12] Y. Y. Zhao and J. Xu, "Using the delayed feedback control and saturation control to suppress the vibration of the dynamical system," *Nonlinear Dynamics*, vol. 67, no. 1, pp. 735–753, 2012.

[13] N. Olgac and B. T. Holm-Hansen, "A novel active vibration absorption technique: delayed resonator," *Journal of Sound and Vibration*, vol. 176, no. 1, pp. 93–104, 1994.

[14] J. J. Liu, Y. X. Sun, and S. Li, "Parameter optimization of time-delayed feedback control for vehicle suspension system in finite frequency band," *J Mech Elec Eng*, vol. 37, no. 1, pp. 54–58, 2020.

[15] G. Yan and M. X. Fang, "Time-delay speed feedback control of vehicle suspension system," *Science Technology and Engineering*, vol. 20, no. 20, pp. 8367–8372, 2020.

[16] Y. W. Qu, C. B. Ren, and J. L. Zhou, "Semi-active suspension control by using dual-delayed feedback based on particle swarm optimization," *Journal of Guangxi University*, vol. 41, no. 5, pp. 1368–1376, 2016.

[17] X. W. Huang and Y. Y. Zhao, "The effect of delayed feedback control on lateral semi-active suspension system for high-speed train," *Advanced Materials Research*, vol. 753-755, pp. 1795–1799, 2013.

[18] W. A. El-Ganaini, A. Kandil, M. Eissa, and M. Kamel, "Effects of delayed time active controller on the vibration of a nonlinear magnetic levitation system to multi excitations," *Journal of Vibration and Control*, vol. 22, no. 5, pp. 1257–1275, 2016.

[19] J. Xu, Y. Chen, and K. W. Chung, "An improved time-delay saturation controller for suppression of nonlinear beam vibration," *Nonlinear Dynamics*, vol. 82, no. 4, pp. 1691–1707, 2015.

[20] F. An, J. Li, and W. Zhang, "Advances and review on the research of the time-delayed acceleration feedback control," *Canadian Journal of Mathematics*, vol. 32, no. 6, pp. 985–991, 2015.

[21] M. Eissa, A. Kandil, W. A. El-Ganaini, and M. Kamel, "Analysis of a nonlinear magnetic levitation system vibrations controlled by a time-delayed proportional-derivative controller," *Nonlinear Dynamics*, vol. 79, no. 2, pp. 1217–1233, 2015.

[22] Z. H. Wang and H. Y. Hu, "Delay-independent stability of retarded dynamic systems of multiple degrees of freedom," *Journal of Sound and Vibration*, vol. 226, no. 1, pp. 57–81, 1999.

[23] Z. H. Wang and H. Y. Hu, "Stability switches of time-delayed dynamic systems with unknown parameters," *Journal of Sound and Vibration*, vol. 233, no. 2, pp. 215–233, 2000.

[24] Q. Wang, C. Ren, J. Zhou, and L. Zhang, "The double-delay reducing vibration control for five-degree-of-freedom half-vehicle model in idle condition," *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 39, no. 1, pp. 203–215, 2019.

[25] K. Zhu, C. B. Ren, and F. Wang, "Research on vibration reduction of 1/4 car model with time delay feedback control," *Journal of Shandong University of Technology*, vol. 30, no. 2, pp. 31–35, 2016.

[26] F. T. K. Au, Y. S. Cheng, and Y. K. Cheung, "Effects of random road surface roughness and long-term deflection of prestressed concrete girder and cable-stayed bridges on impact due to moving vehicles," *Computers & Structures*, vol. 79, no. 8, pp. 853–872, 2001.

[27] W. Schiehlen and B. Hu, "Spectral simulation and shock absorber identification," *International Journal of Non-linear Mechanics*, vol. 38, no. 2, pp. 161–171, 2003.

Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 6621236, 9 pages
https://doi.org/10.1155/2022/6621236

Research Article

A Novel Enhanced Supplier Selection Method Used for Handling Hesitant Fuzzy Linguistic Information

Kuei-Hu Chang [1,2]

[1] *Department of Management Sciences, R.O.C. Military Academy, No. 1, Wei-Wu Rd., Fengshan Dist, Kaohsiung 830, Taiwan*
[2] *Institute of Innovation and Circular Economy, Asia University, Taichung 413, Taiwan*

Correspondence should be addressed to Kuei-Hu Chang; evenken2002@gmail.com

Received 27 June 2021; Revised 1 August 2021; Accepted 15 March 2022; Published 23 April 2022

Academic Editor: Ali Ahmadian

Today's competitive businesses have been shifted from the company-to-company competition model to the supply chain-to-supply chain competition model. The selection of the most suitable supplier determines customer satisfaction and enterprise competitive advantage. However, the typical supplier selection approaches did not consider the ordered weights between the evaluations of attribute values, resulting in distorted assessment result. Moreover, experts often uncertainly decide the exact value of the evaluation attribute's rating, have linguistic term sets equivocation, or give ambiguous information, which increase the difficulty of the supplier evaluation process. To deal with the aforementioned problem, we have proposed a novel enhanced supplier selection method for handling hesitant fuzzy linguistic information. To verify the approach, by taking network security system assessment as an example to explain the use of the proposed novel enhanced supplier selection method, the calculation result is compared with the result of the arithmetic average and symbolic methods. The results show that the proposed novel enhanced supplier selection method is more accurate and reasonable and can better reflect real situations.

1. Introduction

During the advanced information era, competition has shifted from a traditional model of company-versus-company competition to that between supply chains. Adopting the most appropriate suppliers ensures the customer satisfaction and competitiveness of the entire supply chain. Thus, the supplier selection process is especially crucial in the entire supply chain management operation. Supplier selection includes quantitative and qualitative criteria and is classified as a complex multiple attribute decision (MADM) issue. In the process of supplier selection, traditional calculation methods require that the attribute values of possible alternatives be precise. However, in many practical circumstances, the attribute values of possible alternatives include linguistic and equivocal information. Traditional calculation methods cannot effectively address complex MADM problems with fuzzy or ambiguous information. The fuzzy-set-based methods and data envelopment analysis are commonly used approaches to solve complex MADM problems, such as [1]. Thus, many authors used a fuzzy-set-based approach to handle supply-chain-related issues under fuzzy information environments [2–5].

Herrera and Martinez [6] developed the 2-tuple linguistic representation model (2-tuple LRD) to prevent information loss and distortion for computing words of natural languages. This model is constructed by a pair of values: the information linguistic label center and the symbolic translation value. There is extensive research on the 2-tuple LRD. For example, Liu et al. [7] combined interval 2-tuple linguistic variables and the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method to overcome problems of personnel selection that exist in the group decision-making issues. Based on the 2-tuple LRD, Wan [8] introduced an extended 2-tuple hybrid linguistic weighted arithmetic average to effectively handle the problems of personnel selection for MADM issues. Based on the Choquet integral, Beg and Rashid [9] introduced new interval-valued aggregation operators that related to 2-tuple linguistic information to process interval-valued 2-tuple linguistic information. This 2-tuple LRD has been utilized in various disciplines, for instance, supplier selection [10–12], customer collaborative product innovation design [13], computer network security systems [14], semiconductor manufacturing [15], robot selection [16], military simulation training systems [17], and photovoltaic cell manufacturing process [18].

Another shortcoming of traditional calculation methods is that it does not consider the ranking weight of the evaluation attribute value when dealing with issues related to supplier selection. The ordered weight is a crucial factor in MADM problems and preference ranking [19, 20]. Yager [21] firstly introduced the ordered weighted average (OWA) operator to provide a family of parameterized aggregation operators between the maximum and the minimum operators. Work on OWA operators and their application has progressed rapidly. For instance, Yari and Chaji [22] used M-entropy measures to determine the weights of the OWA operator. Based on an optimal deviation mode, Zhou and Chen [23] extended the OWA operator to generalize ordered weighted logarithm aggregation operators for handling group decision-making issues. For handling the multi-attribute group decision-making issues, Wan and Dong [24] developed 4 types of power geometric operators for trapezoidal intuitionistic fuzzy numbers: the power geometric operator, power hybrid geometric operator, power-weighted geometric operator, and power-ordered weighted geometric operator. At present, the OWA operator has widely been utilized, such as target recognition system [25], fighter aircraft airborne radar systems [26], supplier selection [27], thin-film transistor liquid crystal display manufacturing [28], and personnel selection [29]. How to determine the weight of OWA operators is a very critical issue in MADM problems. For a given level of orness, O'Hagan [30] firstly introduced the maximal entropy concept to determine the OWA operators' weights. Extending this concept, Fuller and Majlender [31] derived a polynomial equation based on Lagrange multipliers to determine the optimal weighting vector under maximal entropy. Fuller and Majlender [32] used Kuhn-Tucker second-order sufficiency conditions to determine OWA operator weights; in addition, it was named as a minimal variance OWA (MVOWA) weighting method.

In cases of fuzzy or ambiguous information, experts are unable to determine the exact numerical values of the evaluation data. To manage such information, Torra [33] introduced hesitant fuzzy sets (HFS) and demonstrated that the envelope of HFS is an intuitionistic fuzzy set. Extending HFS to qualitative decision-making problems, Rodriguez et al. [34] firstly proposed hesitant fuzzy linguistic term sets (HFLTSs) to address hesitant linguistic decision-making issues. In the selection and assessment of suppliers, experts are usually hesitant about linguistic term sets (LTSs) in representing the values of evaluated data. For equivocal information, traditional calculation methods are deleted from uncertain information systems, causing information to become distorted and lost in the supplier selection process. Thus, to solve these shortcomings, this study integrates the MVOWA and HFLTS to strengthen the evaluation of supplier selection.

The major contributions of this paper include three innovative points. Firstly, the proposed novel enhanced supplier selection method can effectively handle linguistic information during the information aggregation process. Secondly, the proposed method considers the ordered weight of assessment attribute values and uses MVOWA weights to aggregate the evaluation values of the evaluation attributes in the supplier selection issues. Finally, the proposed method uses the HFLTS to deal with ambiguous information, which can handle hesitant information more flexibly.

The rest of this paper is arranged as follows: Section 2 reviews the research on this topic, including the minimal variability OWA (MVOWA) operator, HFLTS, and 2-tuple LRD. Section 3 introduces the proposed method, which combines the MVOWA and HFLTS for supplier selection problems. In Section 4, an example of network security system selection in the military is illustrated, and the comparisons of the calculated results between other methods are also illustrated. The final section gives the conclusions.

2. Related Works

2.1. MVOWA Operator. The OWA operator was proposed by Yager [21] which is an aggregation operator between the maximum operator and minimum operator, which is defined as follows.

Definition 1 (see [21]). The OWA operator of dimensional n is a mapping OWA: $R^n \longrightarrow R$ that has a correlative weight vector $w = (w_1, w_2, \ldots, w_n)$, such that $w_i \in [0,1]$ and $\sum_{i=1}^{n} w_i = 1$, shown as the following formula:

$$OWA(a_1, a_2, \ldots, a_n) = \sum_{i=1}^{n} w_i b_i, \tag{1}$$

where b_i is the ith largest element in the aggregated objects $(a_1, a_2, \ldots, a_n)$ collection.

Fuller and Majlender [32] used the sufficiency conditions of Kuhn-Tucker second-order to obtain the minimal variability weighting vector of any level of *orness*, named as MVOWA operator weights. The computing process of the MVOWA operator weights is shown as follows:

$$\begin{aligned} \text{Minimizing } Var(w) &= \sum_{i=1}^{n} 1/n (w_i - E(w))^2 \\ &= 1/n \sum_{i=1}^{n} w_i^2 - \left(1/n \sum_{i=1}^{n} w_i\right)^2 \\ &= 1/n \sum_{i=1}^{n} w_i^2 - 1/n^2 \\ \text{Subject to } \alpha &= 1/n - 1 \sum_{i=1}^{n} (n-i) w_i, 0 \le \alpha \le 1, \\ \sum_{i=1}^{n} w_i = 1, \quad & w_i \in [0,1], \quad i = 1, \ldots, n. \end{aligned} \tag{2}$$

For any $\alpha \in [0,1]$, assume that l always exists, the associated weighting vectors are obtained as

$w_j^* = 0$ if $j \notin I_{\{l,n\}}$,

$$w_n^* = \frac{6(n-1)(1-\alpha) - 2(n+2l-4)}{(n-l+1)(n-l+2)}, \tag{3}$$

$$w_l^* = \frac{2(2n+l-2) - 6(n-1)(1-\alpha)}{(n-l+1)(n-l+2)}, \tag{4}$$

$$w_j^* = \frac{j-l}{n-l}w_n + \frac{n-j}{n-l}w_l \text{ if } j \in I_{\{l+1,n+1\}}, \quad (5)$$

where α is the situation parameter, n is the number of attributes, and w is a weight vector.

2.2. HFLTS. According to the linguistic approach and HFS, Rodriguez et al. [34] proposed HFLTSs to handle multi-criteria linguistic decision-making issues. The definitions are shown as follows.

Definition 2 (see [34, 35]). HFLTS H_s is an ordered finite subset of the S continuous linguistic terms, where $S = \{s_0, s_1, \ldots, s_g\}$ is a LTS.

Definition 3 (see [34, 35]). Assumed S be a LTS, $S = \{s_0, s_1, \ldots, s_g\}$, and H_s be a HFLTS. The complement set H_s^c is defined as follows:

$$H_s^c = S - H_s = \{s_i | s_i \in S \text{ and } s_i \notin H_s\}. \quad (6)$$

Definition 4 (see [34, 35]). The intersection and union between 2 arbitrary HFLTSs, H_s^1 and H_s^2, are defined as follows:

$$\begin{aligned} H_s^1 \cap H_s^2 &= \{s_i | s_i \in H_s^1 \text{ and } s_i \in H_s^2\}, \\ H_s^1 \cup H_s^2 &= \{s_i | s_i \in H_s^1 \text{ or } s_i \in H_s^2\}, \end{aligned} \quad (7)$$

where the result is a HFLTS.

Definition 5 (see [34, 35]). Assumed S be a LTS, $S = \{s_0, s_1, \ldots, s_g\}$, and let H_s be an arbitrary HFLTS. The lower bound H_{s^-} and the upper bound H_{s^+} of the HFLTS H_s are defined as follows:

$$\begin{aligned} H_{S^-} &= \min(s_i) = s_j, s_i \in H_S \text{ and } s_i \geq s_j \forall i, \\ H_{S^+} &= \max(s_i) = s_j, s_i \in H_S \text{ and } s_i \leq s_j \forall i. \end{aligned} \quad (8)$$

Definition 6 (see [34, 36]). The envelope of the HFLTS, $env(H_s)$, is a linguistic interval, and the limits are obtained through its upper bound and its lower bound.

$$env(H_s) = [H_{s^-}, H_{s^+}], H_{s^-} \leq H_{s^+} \quad (9)$$

Example 1. Let $S = \left\{ \begin{array}{c} S0 = \text{extremely bad (EB)}, \\ S1 = \text{very bad (VB)}, \\ S2 = \text{bad (B)}, \\ S3 = \text{medium (M)}, \\ S4 = \text{good (G)}, \\ S5 = \text{very good (VG)}, \\ S6 = \text{extremely good (EG)} \end{array} \right\}$ be a LTS and $H_s = \{S4, S5, S6\}$ be a HFLTS of S; its envelope is

$$\begin{aligned} H_{s^-}(S4, S5, S6) &= S4, \\ H_{s^+}(S4, S5, S6) &= S6, \\ env(H_s) &= [S4, S6]. \end{aligned} \quad (10)$$

2.3. 2-Tuple LRD. To extend the symbolic translation concept, Herrera and Martinez [6] introduced the 2-tuple LRD. This method uses the linguistic 2-tuple (s_i, α) to represent the linguistic information, where the semantic element s_i is evaluated by the linguistic variable S, defined in the LTS $S = \{s_0, s_1, \ldots, s_g\}$ and $i \in [0, g]$. α is a numerical value representing symbol translation.

Definition 7 (see [6, 37]). Suppose $\beta \in [0, g]$ be the aggregated results of a set of label indexes are evaluated in a LTS $S = \{s_0, s_1, \ldots, s_g\}$. Assume $i = \text{round}(\beta)$ and $\alpha = \beta - i$ be two values, such that $\alpha \in [-0.5, 0.5)$ and $i \in [0, g]$; then, α is called a translation of symbolic, with round being the usual round operation.

Definition 8 (see [6, 38]). Suppose $S = \{s_0, s_1, \ldots, s_g\}$ be a LTS and $\beta \in [0, g]$ be a value that supports the symbolic aggregation operation result. The function Δ for obtaining the 2-tuple linguistic information that equals to β is defined as follows:

$$\begin{gathered} \Delta\colon [0, g] \longrightarrow S \times [-0.5, 0.5), \\ \Delta(\beta) = (s_i, \alpha), \text{with} \begin{cases} s_i, & i = \text{round}(\beta) \\ \alpha = \beta - i, & \alpha \in [-0.5, 0.5) \end{cases}, \end{gathered} \quad (11)$$

where α is called a translation of symbolic, s_i has the closest index label to β, and round is the usual round operation.

Definition 9 (see [6, 10]). Suppose $x = \{(s_1, \alpha_1), (s_2, \alpha_2), \ldots, (s_n, \alpha_n)\}$ be a 2-tuple set and $w = (w_1, w_2, \ldots, w_n)$ be their associated weights, with $i = 1, 2, \ldots, n$, $w_i \in [0, 1]$, $\sum_{i=1}^n w_i = 1$. The 2-tuple weighted average (2-tuple WA) operator is defined as

$$2\,\text{tuple WA}(X) = n\left(\frac{1}{n}\sum_{i=1}^{n} w_i \Delta^{-1}(s_i, \alpha_i)\right) = \Delta\left(\frac{1}{n}\sum_{i=1}^{n} w_i \beta_i\right). \quad (12)$$

Definition 10 (see [6, 38]). Suppose (s_u, α_1) and (sv, α_2) be two 2 tuples. The 2-tuple linguistic information is compared per an ordinary lexicographic order.

(1) If $u > v$, then $(s_k, \alpha_1) > (s_l, \alpha_2)$.

(2) If $u = v$, then

(a) If $\alpha_1 > \alpha_2$, then $(s_k, \alpha_1) > (s_l, \alpha_2)$
(b) If $\alpha_1 = \alpha_2$, then $(s_k, \alpha_1) = (s_l, \alpha_2)$
(c) If $\alpha_1 < \alpha_2$, then $(s_k, \alpha_1) < (s_l, \alpha_2)$.

(3) If $u < v$, then $(s_k, \alpha_1) < (s_l, \alpha_2)$.

3. Proposed Integration of HFLTS and the MVOWA

With the advent of the information age, the supply chain-versus-supply chain is becoming the new mode of competition instead of the company versus company. The appropriate suppliers must be selected to ensure the customer satisfaction and competitiveness of the entire supply chain. Attributing rating values judgments that are made by experts are usually expressed as LTSs in supplier selection. Then, many authors used LTSs to handle supply-chain-related issues [2, 5, 39–41]. However, the experts are often hesitant between several assessment values when assessing attribute rating values, which increases the complexity and difficulty of supplier selection. Moreover, most studies did not consider the ordered weight of the evaluation attribute rating values in the supplier selection problems (such as [42–44]), which may cause that biased results. Ordered weight is one of several important factors that are used in multiple-attribute decision-making (MADM) and preference ranking [19, 20]. To solve this problem, this study integrates the HFLTS and MVOWA to strengthen the evaluation of supplier selection. The flow diagram of the proposed novel enhanced supplier selection method is shown in Figure 1.

The proposed novel enhanced supplier selection method embraces 7 steps as follows.

Step 1. Determine the possible alternatives and assessment attributes.

Take all of the experts' opinions into account to determine the possible alternatives and assessment attributes.

Step 2. Determine the assessment attributes weights.

Summarize the opinions of the team's experts to obtain the assessment attribute weights.

Step 3. Determine the attribute rating values for possible alternatives.

Based on the team's experts' knowledge and experience, experts use the LTS S to individually determine the attribute rating values.

Step 4. Perform defuzzification.

Apply centroid defuzzification to calculate crisp values. The defuzzified centroid ($C_{\tilde{X}}$) of the fuzzy number $\tilde{X} = (a, b)$ can be calculated by the following formula [45, 46].

$$C_{\tilde{X}} = \frac{(a, b)}{2}, \tag{13}$$

where b is the right boundary and a is the left boundary.

Step 5. Compute the MVOWA weights.

Use equations (3)–(5) to compute the MVOWA weights.

Step 6. Using MVOWA weights to compute the aggregated value.

Based on Step 4 and Step 5, use (1) to compute the aggregated evaluation values of the alternative using MVOWA weights.

Step 7. Analyze the calculation results, and select the best alternative.

Based on the calculation results of Step 6, rank the alternative order according to the aggregated evaluation values of the alternative.

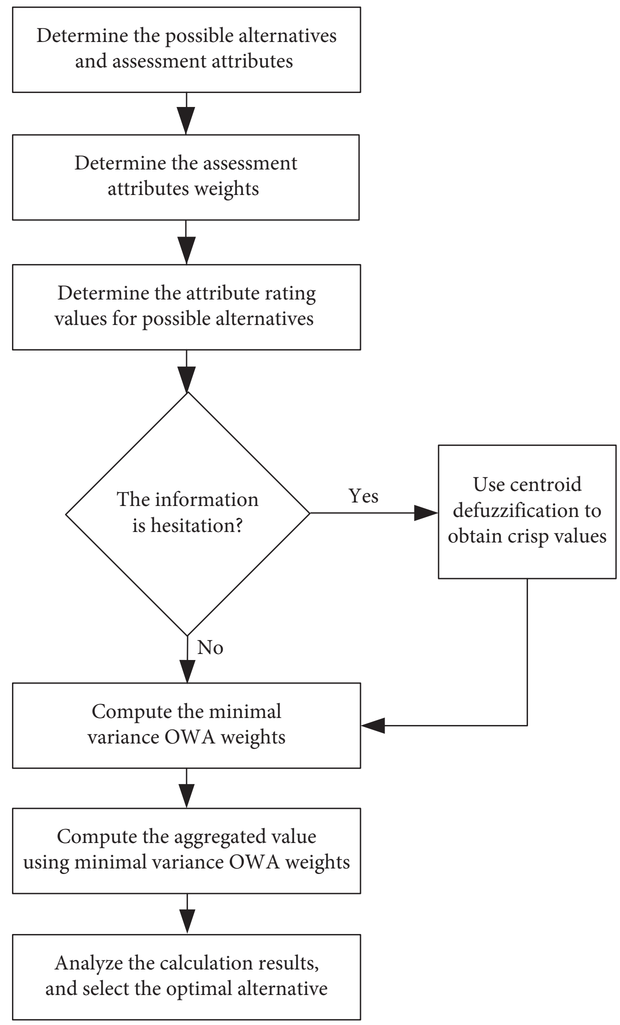


Figure 1: Flow diagram of the proposed novel enhanced supplier selection method.

4. Case Study

This study uses an illustrative example of selecting a network security system in the military from Zhang [14] to demonstrate the proposed procedure. After a preliminary screen, the network security system considers 4 alternatives, A_i ($i = 1, 2, 3, 4$), for further evaluation. The team of experts must make a decision according to the 5 following assessment attributes: tactics ($G1$), technology ($G2$), economy ($G3$), logistics ($G4$), and strategy ($G5$). The 4 possible alternatives are evaluated using the linguistic information per the LTS S. S can be defined as

$$\begin{aligned} S = \{&S0 = \text{extremely bad (EB)}, S1 = \text{very bad (VB)},\\ &S2 = \text{bad (B)}, S3 = \text{medium (M)}, \quad S4 = \text{good (G)},\\ &S5 = \text{very good (VG)}, S6 = \text{extremely good (EG)}\}. \end{aligned} \tag{14}$$

The network security system selection team comprises 3 decision-makers, each of whom evaluates the attributes rating values for the 4 alternatives according to the LTS S, as shown in Table 1. The weight vector of the attributes is $w = [0.10, 0.15, 0.20, 0.30, 0.25]$.

4.1. Solution Based on the Typical Arithmetic Average Method. Although the mathematical operation of the typical arithmetic average method is simpler, it requires that all of the data be certain. In part, the attribute values that were provided by expert P3 were ambiguous. Therefore, typical arithmetic average method only considered the certain information that were provided by experts P1 and P2. The rating values of the network security system selection by the typical arithmetic average method are shown in Table 2.

Now, the ranking of the alternatives is Alternative 1 ≻ Alternative 4 ≻ Alternative 3 ≻ Alternative 2.

Thus, the most suitable alternative is Alternative 1.

4.2. Solution Based on the Symbolic Method [6, 47]. Delgado et al. [47] firstly defined the symbolic method. This method aggregated linguistic variables in a convex combination to correspond to the linguistic terms. However, this method cannot handle situations in which experts equivocate with regard to their preferences for objects in supplier selection. In this case, partially data from expert P3 were ambiguous. Therefore, only considered the certain information that were provided by experts P1 and P2. The aggregate evaluation values of the network security system by the symbolic method are shown in Table 3.

This section uses the assessment attribute $G1$ and the aggregated evaluation value for alternative 1 which is $S4$ in this illustrative example; the computation process is as follows:

$$\begin{aligned}
&C^2\left\{\left(\frac{1}{2}, S5\right), \left(\frac{1}{2}, S3\right)\right\} \\
&= \left(\frac{1}{2} \otimes S5\right) \oplus \left(1 - \frac{1}{2}\right) \otimes (S3) = Sk, \\
&k = \min\{6,\ 3 + \text{round}\,(0.5n\,(5-3))\} = 4, \\
&\Rightarrow C^2\left\{\left(\frac{1}{2}, S5\right), \left(\frac{1}{2}, S3\right)\right\} = S4.
\end{aligned} \tag{15}$$

This section uses an aggregate rating value of $S4$ for alternative 1 in this illustrative example; the computing process is as follows:

$$\begin{aligned}
&C^5\{(0.10, S4), (0.15, S5), (0.20, S3), (0.30, S5), (0.25, S4)\} \\
&= (0.10 \otimes S4) \oplus (1 - 0.10) \\
&\otimes C^4\{(0.167, S5), (0.222, S3), (0.333, S5), (0.278, S4)\}, \\
&C^4\{(0.167, S5), (0.222, S3), (0.333, S5), (0.278, S4)\} \\
&= (0.167 \otimes S5) \oplus (1 - 0.167), \\
&\otimes C^3\{(0.267, S3), (0.4, S5), (0.333, S4)\}, \\
&C^3\{(0.267, S3), (0.4, S5), (0.333, S4)\} \\
&= (0.267 \otimes S3) \oplus (1 - 0.267) \otimes C^2\{(0.545, S5), (0.455, S4)\}, \\
&C^2\{(0.545, S5), (0.455, S4)\} = (0.545 \otimes S5) \oplus (1 - 0.545) \otimes S4 = Sk, \\
&k = \min\{6,\ 4 + \text{round}\,(0.545n\,(5-4))\} = 5, \\
&\Rightarrow C^2\{(0.545, S5), (0.455, S4)\} = S5, \\
&C^3\{(0.267, S3), (0.4, S5), (0.333, S4)\} = (0.267 \otimes S3) \oplus (1 - 0.267) \otimes S5, \\
&k = \min\{6,\ 3 + \text{round}\,(0.267n\,(5-3))\} = 4, \\
&\Rightarrow C^3\{(0.267, S3), (0.4, S5), (0.333, S4)\} = S4, \\
&C^4\{(0.167, S5), (0.222, S3), (0.333, S5), (0.278, S4)\} \\
&= (0.167 \otimes S5) \oplus (1 - 0.167) \otimes S4, \\
&k = \min\{6,\ 4 + \text{round}\,(0.167n\,(5-4))\} = 4, \\
&\Rightarrow C^4\{(0.167, S5), (0.222, S3), (0.333, S5), (0.278, S4)\} = S4, \\
&C^5\{(0.10, S4), (0.15, S5), (0.20, S3), (0.30, S5), (0.25, S4)\} \\
&= (0.10 \otimes S4) \oplus (1 - 0.10) \otimes S4, \\
&k = \min\{6,\ 4 + \text{round}\,(0.10n\,(4-4))\} = 4 \\
&\Rightarrow C^5\{(0.10, S4), (0.15, S5), (0.20, S3), (0.30, S5), (0.25, S4)\} = S4.
\end{aligned} \tag{16}$$

Table 1: Attribute rating values for four alternatives.

Attribute		G1	G2	G3	G4	G5
Alternative 1	P1	S5	S6	S3	S4	S6
	P2	S3	S4	S2	S6	S2
	P3	S1	S5	S6	S5	S4
Alternative 2	P1	S3	S1	S2	S1	S0
	P2	S6	S6	S5	S3	S1
	P3	S2	S4	S1	S4	S3
Alternative 3	P1	S4	S0	S6	S3	S2
	P2	S2	S3	S6	S1	S3
	P3	[S4, S5]	S2	S5	[S1, S2]	S6
Alternative 4	P1	S1	S5	S3	S2	S3
	P2	S1	S0	S4	S4	S6
	P3	[S5, S6]	S1	S0	[S4, S6]	S2

Table 2: Network security system selection by the typical arithmetic average method.

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Rating values	S4.15	S2.4	S2.95	S3.2

Table 3: Aggregate evaluation values of the network security system by the symbolic method.

Attribute	G1	G2	G3	G4	G5	Aggregate rating values
Alternative 1	S4	S5	S3	S5	S4	S4
Alternative 2	S5	S4	S4	S2	S1	S3
Alternative 3	S3	S2	S6	S2	S3	S3
Alternative 4	S1	S3	S4	S3	S5	S4

4.3. Solution Based on the Proposed Novel Enhanced Supplier Selection Method. The proposed novel enhanced supplier selection method integrates the MVOWA and HFLTS to strengthen the evaluation of supplier selection, based on Steps 1 to 7 (Section 3). First, experts come together to discuss the selection of a network security system, including 4 possible alternatives and 5 assessment attributes (Step 1). Then, calculate the aggregated value of the experts' opinions and the assessment attributes weights ($w = [0.10, 0.15, 0.20, 0.30, 0.25]$) (Step 2). Moreover, the attribute rating values for the alternatives are determined per the experts' knowledge and experience (see Table 1) (Step 3). The remaining steps are described as follows:

Step 4 (defuzzification). This paper used the centroid defuzzification method to calculate crisp values. According to equation (9), the defuzzification attribute rating values for the 4 alternatives are calculated (see Table 4).

Step 5 (compute the MVOWA weights). Based on equations (3)–(5), the MVOWA weights are computed for $n = 5$, as shown in Table 5.

For example, when $n = 5$ and $\alpha = 0.7$, by equation (3), it is found that

Table 4: Defuzzification of attribute rating values for the four alternatives.

Attribute		G1	G2	G3	G4	G5
Alternative 1	P1	S5	S6	S3	S4	S6
	P2	S3	S4	S2	S6	S2
	P3	S1	S5	S6	S5	S4
Alternative 2	P1	S3	S1	S2	S1	S0
	P2	S6	S6	S5	S3	S1
	P3	S2	S4	S1	S4	S3
Alternative 3	P1	S4	S0	S6	S3	S2
	P2	S2	S3	S6	S1	S3
	P3	S4.5	S2	S5	S1.5	S6
Alternative 4	P1	S1	S5	S3	S2	S3
	P2	S1	S0	S4	S4	S6
	P3	S5.5	S1	S0	S5	S2

Table 5: MVOWA weights when $n = 5$.

Alpha	Weight				
	w1	w2	w3	w4	w5
0	0.000	0.000	0.000	0.000	1.000
0.1	0.000	0.000	0.033	0.333	0.633
0.2	0.000	0.040	0.180	0.320	0.460
0.3	0.040	0.120	0.200	0.280	0.360
0.4	0.120	0.160	0.200	0.240	0.280
0.5	0.200	0.200	0.200	0.200	0.200
0.6	0.280	0.240	0.200	0.160	0.120
0.7	0.360	0.280	0.200	0.120	0.040
0.8	0.460	0.320	0.180	0.040	0.000
0.9	0.633	0.333	0.033	0.000	0.000
1	1.000	0.000	0.000	0.000	0.000

$$w_5 = \frac{6(n-1)(1-\alpha) - 2(n+2l-4)}{(n-l+1)(n-l+2)} = \frac{6(5-1)(1-0.7) - 2(5+2-4)}{(5-1+1)(5-1+2)} = 0.040. \tag{17}$$

By (4), it is found that

$$w_1 = \frac{2(2n+l-2) - 6(n-1)(1-\alpha)}{(n-l+1)(n-l+2)} = \frac{2(2\times 5+1-2) - 6(5-1)(1-0.7)}{(5-1+1)(5-1+2)} = 0.360. \tag{18}$$

Therefore, by (5), it is found that

$$\begin{aligned} w_2 &= \frac{n-j}{n-l}w_l + \frac{j-l}{n-l}w_n = \frac{5-2}{5-1}w_1 + \frac{2-1}{5-1}w_5 = 0.280, \\ w_3 &= \frac{n-j}{n-l}w_l + \frac{j-l}{n-l}w_n = \frac{5-3}{5-1}w_1 + \frac{3-1}{5-1}w_5 = 0.200, \\ w_4 &= \frac{n-j}{n-l}w_l + \frac{j-l}{n-l}w_n = \frac{5-4}{5-1}w_1 + \frac{4-1}{5-1}w_5 = 0.120. \end{aligned} \tag{19}$$

Step 6 (using MVOWA weights to compute the aggregated value). Based on Table 4, Table 5, and equation (1), the

Table 6: Summarized evaluation values of the network security system by the proposed method.

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
$\alpha = 0.5$	0.857	0.517	0.640	0.607
$\alpha = 0.6$	0.963	0.561	0.733	0.699
$\alpha = 0.7$	1.070	0.606	0.827	0.792
$\alpha = 0.8$	1.174	0.655	0.928	0.896
$\alpha = 0.9$	1.307	0.707	1.041	1.017

Table 7: Ranking of the three methods.

Alternative	Typical arithmetic average method	Ranking typical arithmetic average method	Symbolic method	Ranking symbolic method	Proposed method					Ranking proposed method
					$\alpha = 0.5$	$\alpha = 0.6$	$\alpha = 0.7$	$\alpha = 0.8$	$\alpha = 0.9$	
Alternative 1	$S4.15$	1	$S4$	1	0.857	0.963	1.070	1.174	1.307	1
Alternative 2	$S2.40$	4	$S3$	3	0.517	0.561	0.606	0.655	0.707	3
Alternative 3	$S2.95$	3	$S3$	3	0.640	0.733	0.827	0.928	1.041	4
Alternative 4	$S3.20$	2	$S4$	1	0.607	0.699	0.792	0.896	1.017	2

Table 8: Differences in the main advantages of the three methods.

Consideration factor	Method		
	Typical arithmetic average method	Symbolic method	Proposed novel enhanced supplier selection method
Linguistic information	No	Yes	Yes
Order weight	No	No	Yes
Hesitant information	No	No	Yes

aggregate evaluation values of the network security system, based on the MVOWA weights ($\alpha = 0.5, 0.6, 0.7, 0.8, 0.9$), are calculated and shown in Table 6.

Step 7 (analyze the calculation results and select the best alternative). According to the calculation results of Step 6, the fuzzy majority rule is used as the proposed order: Alternative 1 ≻ Alternative 3 ≻ Alternative 4 ≻ Alternative 2.

4.4. Comparisons and Discussion. In order to further evaluate the effectiveness of the proposed novel enhanced supplier selection method, Section 4 illustrates a verification example of implementing a network security system in the military. This study also compares the experimental results with those of the typical arithmetic average and symbolic methods. The case data of the network security system are shown in Table 1, and the ranking of the 3 methods is shown in Table 7. The main differences between our method and the other solutions are described in Table 8. According to the comparison, the proposed integration of the HFLTS and MVOWA has several advantages.

4.4.1. Linguistic Information Considered. Supplier selection is an MADM problem and includes a significant amount of quantitative and qualitative data. Experts use LTSs to express the assessment attributes values to more reasonably reflect the actual situation. However, the attribute values of the possible alternative are required to be exact numerical values in the typical arithmetic average method, rendering it unable to handle linguistic information. The proposed method and symbolic method can incorporate linguistic information in the information aggregation process.

4.4.2. Ordered Weight Considered. The ordered weight is one of several important influencing factors that are used in multiple-attribute decision-making (MADM) and preference ranking [19, 20]. However, the traditional arithmetic average and symbolic methods did not consider the ordered weights of evaluation attribute values in the supplier selection issues, which will lead to deviations in the evaluation results. The proposed novel enhanced supplier selection method uses MVOWA weights to aggregate the evaluation values of the evaluation attributes. Thus, our approach is more suitable than the traditional arithmetic average and symbolic methods for supplier selection when considering ambiguous information.

4.4.3. Equivocal Information Considered. The typical arithmetic average method and symbolic method require that the attribute values of possible alternatives be precise and constitute a single LTS. However, an expert is sometimes uncertain about the exact value and single LTS of the assessment attribute data in supplier selection. For ambiguous information, the traditional arithmetic average and symbolic methods deleted assessment attribute data directly, decreased the samples number, and removed valuable information. The proposed novel enhanced supplier selection method uses the HFLTS to deal with ambiguous information. Thus, all of the information that the experts provide will be considered, and the results more accurately reflect the actual situation.

5. Conclusion

Supplier selection is a critical part of supply chain management and influences the successful operation of the supply chain. Selecting the most suitable supplier will ensure the competitive advantages and sustainable development of the entire supply chain. However, the typical supplier selection approaches did not consider the ordered weights between the evaluations of attribute values. The ordered weights are crucial factors in supplier selection problems, which will influence the assessment results of supplier selection. On the other hand, the experts are often hesitant between several assessment values when assessing attribute rating values, which increases the complexity and difficulty of supplier selection. To strengthen the evaluation of supplier selection, this study has integrated the HFLTS and MVOWA methods to select the most suitable supplier. Moreover, a network security system selection problem in the military was used as an illustrative example to compare the typical arithmetic average method, symbolic method, and our proposed approach. The simulation results showed that the proposed novel enhanced supplier selection method can provide more accurate and reasonable outcomes and can better reflect the actual situation than the typical arithmetic average method and symbolic method.

There are several advantages of integrating the MVOWA and HFLTS as follows. First, the proposed novel enhanced supplier selection method can effectively handle linguistic information in supplier selection. Moreover, our approach considers the ordered weight of assessment attribute values in the supplier selection issues. Finally, our method can more flexibly and precisely handle hesitant information. Thus, all information that the experts provide will be considered, and no useful information is lost. In the future, in further research, we expect to perform a more empirical study in a specific industry and extend the concept of our approach to address other decision-making issues. In addition, future research can explore using different algorithms to calculate the order weights in MADM problems.

Data Availability

The supplier selection data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank the Ministry of Science and Technology, Taiwan, for financially supporting this research under Contract No. MOST 109-2410-H-145-002 and MOST 110-2410-H-145-001.

References

[1] H. H. Lai, K. H. Chang, and C. L. Lin, "A novel method for evaluating dredging productivity using a data envelopment analysis-based technique," *Mathematical Problems in Engineering*, vol. 2019, pp. 1–22, Article ID 5130835, 2019.

[2] F. Farajpour and A. Yousefli, "Information flow in supply chain: a fuzzy TOPSIS parameters ranking," *Uncertain Supply Chain Management*, vol. 6, no. 2, pp. 181–194, 2018.

[3] C. Y. Chiu, Y. Lin, and M. F. Yang, "Applying fuzzy multi-objective integrated logistics model to green supply chain problems," *Journal of Applied Mathematics*, vol. 2014, Article ID 767095, 2014.

[4] K. Lu, H. Liao, and E. K. Zavadskas, "An overview of fuzzy techniques in supply chain management: bibliometrics, methodologies, applications and future directions," *Technological and Economic Development of Economy*, vol. 27, no. 2, pp. 402–458, 2021.

[5] K. H. Chang, "A novel supplier selection method that integrates the intuitionistic fuzzy weighted averaging method and a soft set with imprecise data," *Annals of Operations Research*, vol. 272, no. 1-2, pp. 139–157, 2019.

[6] F. Herrera and L. Martinez, "A 2-tuple fuzzy linguistic representation model for computing with words," *IEEE Transactions on Fuzzy Systems*, vol. 8, no. 6, pp. 746–752, 2000.

[7] H. C. Liu, J. T. Qin, L. X. Mao, and Z. Y. Zhang, "Personnel selection using interval 2-tuple linguistic VIKOR method," *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 25, no. 3, pp. 370–384, 2015.

[8] S.-P. Wan, "2-tuple linguistic hybrid arithmetic aggregation operators and application to multi-attribute group decision making," *Knowledge-Based Systems*, vol. 45, pp. 31–40, 2013.

[9] I. Beg and T. Rashid, "Aggregation operators of interval-valued 2-tuple linguistic information," *International Journal of Intelligent Systems*, vol. 29, no. 7, pp. 634–667, 2014.

[10] X. Deng, J. Wang, and G. Wei, "Multiple attribute decision making based on power muirhead mean operators under 2-tuple linguistic pythagorean fuzzy environment," *Cognitive Computation*, vol. 12, no. 6, pp. 1276–1298, 2020.

[11] T. C. Wen, K. H. Chang, and H. H. Lai, "Integrating the 2-tuple linguistic representation and soft set to solve supplier selection problems with incomplete information," *Engineering Applications of Artificial Intelligence*, vol. 87, Article ID 103248, 2020.

[12] J. Wang, J. P. Lu, G. W. Wei, R. Lin, and C. Wei, "Models for MADM with single-valued neutrosophic 2-tuple linguistic Muirhead mean operators," *Mathematics*, vol. 7, no. 5, p. 442, 2019.

[13] A. J. Liu, Q. Y. Zhu, H. Y. Liu, H. Lu, and S. B. Tsai, "A novel approach based on Kano model, interval 2-tuple linguistic representation model, and prospect theory for apperceiving key customer requirements," *Mathematical Problems in Engineering*, vol. 2018, Article ID 8192819, 2018.

[14] S. Zhang, "A model for evaluating computer network security systems with 2-tuple linguistic information," *Computers & Mathematics with Applications*, vol. 62, no. 4, pp. 1916–1922, 2011.

[15] Y. C. Chang, K. H. Chang, and C. Y. Chen, "Risk assessment by quantifying and prioritizing 5S activities for semiconductor manufacturing," *Proceedings of the Institution of*

Mechanical Engineers - Part B: Journal of Engineering Manufacture, vol. 227, no. 12, pp. 1874–1887, 2013.

[16] A. A. Khan, M. Qiyas, S. Abdullah, J. C. Luo, and M. Bano, "Analysis of robot selection based on 2-tuple picture fuzzy linguistic aggregation operators," *Mathematics*, vol. 7, no. 10, p. 1000, 2019.

[17] K. H. Chang, Y. C. Chang, and H. Y. Chung, "A novel AHP-based benefit evaluation model of military simulation training systems," *Mathematical Problems in Engineering*, vol. 2015, Article ID 956757, 2015.

[18] T. C. Wen, H. Y. Chung, K. H. Chang, and Z. S. Li, "A flexible risk assessment approach integrating subjective and objective weights under uncertainty," *Engineering Applications of Artificial Intelligence*, vol. 103, Article ID 104310, 2021.

[19] K. H. Chang and T. C. Wen, "An innovative approach integrating 2-tuple and LOWGA operators in process failure mode and effects analysis," *International Journal of Innovative Computing, Information and Control*, vol. 8, pp. 747–761, 2012.

[20] K.-H. Chang, T.-C. Wen, T. C. Wen, and C. H. Cheng, "A novel efficient approach for DFMEA combining 2-tuple and the OWA operator," *Expert Systems with Applications*, vol. 37, no. 3, pp. 2362–2370, 2010.

[21] R. R. Yager, "On ordered weighted averaging aggregation operators in multicriteria decisionmaking," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 18, no. 1, pp. 183–190, 1988.

[22] G. Yari and A. Chaji, "Determination of ordered weighted averaging operator weights based on the M-entropy measures," *International Journal of Intelligent Systems*, vol. 27, no. 12, pp. 1020–1033, 2012.

[23] L. G. Zhou and H. Y. Chen, "Generalized ordered weighted logarithm aggregation operators and their applications to group decision making," *International Journal of Intelligent Systems*, vol. 25, no. 7, pp. 683–707, 2010.

[24] S. P. Wan and J. Y. Dong, "Power geometric operators of trapezoidal intuitionistic fuzzy numbers and application to multi-attribute group decision making," *Applied Soft Computing*, vol. 29, pp. 153–168, 2015.

[25] X. Mi, T. Lv, Y. Tian, and B. Kang, "Multi-sensor data fusion based on soft likelihood functions and OWA aggregation and its application in target recognition system," *ISA Transactions*, vol. 112, pp. 137–149, 2021.

[26] Y. C. Chang, K. H. Chang, and C. S. Liaw, "Innovative reliability allocation using the maximal entropy ordered weighted averaging method," *Computers & Industrial Engineering*, vol. 57, no. 4, pp. 1274–1281, 2009.

[27] M. Naeem, M. Qiyas, and S. Abdullah, "An approach of interval-valued picture fuzzy uncertain linguistic aggregation operator and their application on supplier selection decision-making in logistics service value concretion," *Mathematical Problems in Engineering*, vol. 2021, Article ID 8873230, 2021.

[28] K.-H. Chang, "Evaluate the orderings of risk for failure problems using a more general RPN methodology," *Microelectronics Reliability*, vol. 49, no. 12, pp. 1586–1596, 2009.

[29] T. C. Wen, K. H. Chang, and H. H. Lai, "Improving personnel selection by combining the minimal variance OWA operator and IPA," *Journal of Intelligent and Fuzzy Systems*, vol. 35, no. 6, pp. 6229–6239, 2018.

[30] M. O. Hagan, "Aggregating template or rule antecedents in real time expert systems with fuzzy set logic," in *Proceedings of the 22th Annual IEEE Asilomar Conference on Signals, Systems*, pp. 681–689, Computers Pacific Grove, CA, USA, 1988.

[31] R. Fullér and P. Majlender, "An analytic approach for obtaining maximal entropy OWA operator weights," *Fuzzy Sets and Systems*, vol. 124, no. 1, pp. 53–57, 2001.

[32] R. Fullér and P. Majlender, "On obtaining minimal variability OWA operator weights," *Fuzzy Sets and Systems*, vol. 136, no. 2, pp. 203–215, 2003.

[33] V. Torra, "Hesitant fuzzy sets," *International Journal of Intelligent Systems*, vol. 25, no. 6, pp. 529–539, 2010.

[34] R. M. Rodriguez, L. Martinez, and F. Herrera, "Hesitant fuzzy linguistic term sets for decision making," *IEEE Transactions on Fuzzy Systems*, vol. 20, no. 1, pp. 109–119, 2012.

[35] S.-M. Chen and J.-A. Hong, "Multicriteria linguistic decision making based on hesitant fuzzy linguistic term sets and the aggregation of fuzzy sets," *Information Sciences*, vol. 286, pp. 63–74, 2014.

[36] R. M. Rodríguez, L. Martínez, and F. Herrera, "A group decision making model dealing with comparative linguistic expressions based on hesitant fuzzy linguistic term sets," *Information Sciences*, vol. 241, pp. 28–42, 2013.

[37] Y. Dong, W.-C. Hong, and Y. Xu, "Measuring consistency of linguistic preference relations: a 2-tuple linguistic approach," *Soft Computing*, vol. 17, no. 11, pp. 2117–2130, 2013.

[38] Q. Wang, D. D. Wang, Y. Zhang, and X. H. Chen, "Multi-criteria group decision making method based on interval 2-tuple linguistic information and Choquet integral aggregation operators," *Soft Computing*, vol. 19, no. 2, pp. 389–405, 2015.

[39] K. H. Chang, K. Chain, T. C. Wen, and G. K. Yang, "A novel general approach for solving a supplier selection problem," *Journal of Testing and Evaluation*, vol. 44, no. 5, pp. 1911–1924, 2016.

[40] C. N. Wang, N. A. T. Nguyen, T. T. Dang, and C. M. Lu, "A compromised decision-making approach to third-party logistics selection in sustainable supply chain using fuzzy AHP and fuzzy VIKOR methods," *Mathematics*, vol. 9, no. 8, p. 886, 2021.

[41] M. Yazdani, P. Zarate, A. Coulibaly, and E. K. Zavadskas, "A group decision making support system in logistics and supply chain management," *Expert Systems with Applications*, vol. 88, pp. 376–392, 2017.

[42] P. Liu and H. Gao, "A novel green supplier selection method based on the interval type-2 fuzzy prioritized Choquet Bonferroni means," *IEEE/CAA Journal of Automatica Sinica*, vol. 8, no. 9, pp. 1549–1566, 2021.

[43] M. M. Zheng, H. Zhou, P. Jiang, E. S. Pan, S. T. Zhao, and K. Wu, "Supplier selection problem for multiple projects with uncertain demand and project life cycles," *Computers & Operations Research*, vol. 132, Article ID 105312, 2021.

[44] Y. Q. Ou and B. Liu, "Exploiting the chain convenience store supplier selection based on ANP-MOP model," *Mathematical Problems in Engineering*, vol. 2021, Article ID 5582067, 2021.

[45] J.-S. Yao and J. Chiang, "Inventory without backorder with fuzzy total cost and fuzzy storing cost defuzzified by centroid and signed distance," *European Journal of Operational Research*, vol. 148, no. 2, pp. 401–409, 2003.

[46] K.-H. Chang, "Enhanced assessment of a supplier selection problem by integration of soft sets and hesitant fuzzy linguistic term set," *Proceedings of the Institution of Mechanical Engineers - Part B: Journal of Engineering Manufacture*, vol. 229, no. 9, pp. 1635–1644, 2015.

[47] M. Delgado, J. L. Verdegay, and M. A. Vila, "On aggregation operations of linguistic labels," *International Journal of Intelligent Systems*, vol. 8, no. 3, pp. 351–370, 1993.

Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 6424869, 24 pages
https://doi.org/10.1155/2022/6424869

Research Article

A Novel Smart Production Management System for the Enhancement of Industrial Sustainability in Industry 4.0

Varun Tripathi,[1] Somnath Chattopadhyaya,[2] A. K. Mukhopadhyay,[3] Suvandan Saraswat,[4] Shubham Sharma,[5,6] Changhe Li,[7] S. Rajkumar,[8] and Fasika Bete Georgise[9]

[1]*Department of Mechanical Engineering, Accurate Institute of Management & Technology, Greater Noida, Uttar Pradesh, India*
[2]*Indian Institute of Technology (ISM), Dhanbad, India*
[3]*Department of Mining Machinery Engineering, Indian Institute of Technology (ISM), Dhanbad, India*
[4]*Department of Mechanical Engineering, JSS Academy of Technical Education, Noida, India*
[5]*Department of Mechanical Engineering, IK Gujral Punjab Technical University, Main Campus, Kapurthala 144603, India*
[6]*Department of Mechanical Engineering, University Centre for Research and Development (UCRD), Chandigarh University, Mohali 140413, Punjab, India*
[7]*School of Mechanical and Automotive Engineering, Qingdao University of Technology, Qingdao 266520, China*
[8]*Department of Mechanical Engineering, Faculty of Manufacturing, Institute of Technology, Hawassa University, Hawassa, Ethiopia*
[9]*Department of Industrial Engineering, Faculty of Manufacturing, Institute of Technology, Hawassa University, Hawassa, Ethiopia*

Correspondence should be addressed to Shubham Sharma; shubhamsharmacsirclri@gmail.com and S. Rajkumar; rajkumar@hu.edu.et

Received 28 October 2021; Accepted 24 February 2022; Published 13 April 2022

Academic Editor: Kuei-Hu Chang

In industry 4.0, shop floor management teams are increasingly focused on developing an unprecedented strategy to avoid financial losses and address the challenges and problems encountered in operations management. In the present scenario, the management teams use various process optimization approaches for operational control, including lean manufacturing, smart manufacturing, the internet of things, and artificial intelligence. The process optimization approach is used to maximize productivity within limited constraints on the shop floor. The present research aims to develop a smart production management system and suggest an efficient process optimization approach to enhancing industrial sustainability by identifying problems and challenges encountered in the complex shop-floor conditions in industry 4.0. The developed production management system has been prepared by classifying the challenges and problems found in the previous research work and organizing brainstorming sessions. The developed management system has been validated by a comprehensive investigation of a case study of an earthmoving machinery manufacturing unit. The analysis showed that the developed system could enhance operation excellence and industrial sustainability in industry 4.0 by optimizing the utilization of resources on the shop floor within limited constraints. The authors of the present article strongly believe that the developed production management system will improve operational excellence and would be beneficial for industry personnel and researchers in controlling operations management in shop floor management of heavy machinery manufacturing, including industry 4.0.

1. Introduction

In industry 4.0, the advantages of the process optimization methods have attracted industry persons and young researchers' attention in the shop floor management domain. Shop floor management, as a key component in industries, is used to maintain industrial sustainability and the stability of resource availability [1]. Process optimization approaches are used to improve productivity with limited resources. Process optimization thinking has focused more on increasing the efficiency of production processes [2]. At present time, several methods are used for process optimization in industries including lean manufacturing, smart manufacturing, internet of things, and artificial intelligence. The process optimization approach is the prevalent strategy in industry 4.0, and it is implemented to improve productivity and optimization of resources [3]. In addition, another author argued that the process optimization approach is applied to meet customer demand in terms of the product as the process optimization approach improves productivity by eliminating waste to achieve the industry's goal [4]. Striving this goal also provides a number of other benefits, which may include production time reduction and increased quality of the production processes, leading to a higher satisfaction level of customers in terms of product. Figure 1 shows the objectives of process optimization approaches in industry 4.0. According to Tripathi et al. [5], process optimization methods are implemented to improve production efficiency. The main advantages of the process optimization approach in industry 4.0 are below:

(1) To achieve a sustainable production management system
(2) To maximize the production rate and production flexibility within available resources
(3) To improve the flexibility, agility, customization, and adaptability in industry 4.0
(4) Ease of implementing industry 4.0 technologies on the production shop floor to the industry individuals

To evaluate the efficiency of production processes, overall production processes and activities are categorized. The categorization helps know if the activities involved contribute to the production process; if so, the activity adds value to the production and is known as value-added activities; and if not, the activity is non-value-added (NVA) and known as non-value-added activities (NVAA) [6]. The elimination of non-value-added activities continuously improves production processes and makes it easier to control production performance for shop floor management [7].

The shop floor management team encourages the synergistic implementation of the Lean concept with industry 4.0 technologies to eliminate waste and enhance industrial sustainability. For this, new models and strategies have been developed by previous researchers to strengthen operational performance and to know the present condition of industry 4.0 technologies. Sony et al. [8] proposed an integration model of industry 4.0 and lean management. The model was developed by reviewing previous literature, and in the study, vertical, horizontal, and end-to-end engineering models were integrated with the lean management methodology. This study provided 15 research propositions to advance the integrative mechanism of industry 4.0 and lean management for enhancing financial profitability by better utilization of resources. Tortorella et al. [9] examined the role of industry 4.0 technologies on the relationship between operational performance and lean production within Brazil. The study has organized a survey on implementing lean and industry

Figure 1: Aim of process optimization approach in industry 4.0.

4.0 technologies by performance indicators, including productivity, quality, delivery, safety, and inventory. The collected data has been collected through questionnaires and analyzed by multivariate analysis and contingency theory. The result of the study revealed that entirely technological adoption could not be able to enhance operational performance. However, lean helps in process improvement and support in controlling operation management in industry 4.0. Kamble et al. [10] combined the empirical and exploratory research design to develop a framework for identifying and validating the performance measure for evaluating smart manufacturing systems in Indian small, medium, and microenterprises of auto-components. The data was collected by questionnaire on ten performance dimensions: flexibility, cost, quality, integration, time, optimized productivity, computing, real-time diagnosis and prognosis, and social and ecological sustainability. The result of the study revealed that the proposed performance system was proved able to evaluate the smart manufacturing system and its investments.

Amjad et al. [11] developed a comprehensive implementation framework that integrated lean, green manufacturing, and industry 4.0 effectively. The developed framework was validated by implementing it in an auto-parts manufacturing firm. The result of the study showed that reduced the value-added time, lead time, non-value-added time, and greenhouses gases emission effectively by 24.68%, 25.60%, 56.20%, and 55%, respectively. The developed framework was able to achieve optimized and cleaner production with automation-based rapid and environmentally conscious manufacturing. Tortorella et al. [12] investigated the relationship between lean production and industry 4.0 through a survey organized with 110 different sizes and sectors of Brazilian manufacturing companies. The data were collected by a questionnaire and analyzed with the help of multivariate analysis. The result of the study indicates that lean production was positively associated with industry 4.0 techniques, and their integrated implementation can lead to enhance performance improvements.

Dahmani et al. [13] developed an eco-design industry 4.0 framework for investigating the relationship between industry 4.0 strategies and lean eco-design. The developed framework was based on the synergetic use of eco-design, industry 4.0, and lean design. The study revealed that the developed framework was able to provide cleaner products using suitable processes to help manufacturers design products and fulfill customer expectations. Varela et al. [14] proposed a structural equation model to quantitatively measure the effect of lean manufacturing and industry 4.0 on sustainability. The data was collected by 252 questionnaires obtained from industrial companies located in the Iberian Peninsula. The result of the study showed that it was not conclusive that lean manufacturing was correlated with any pillars of sustainability including environmental, economic, and social, whereas industry 4.0 showed a strong correlation with sustainability pillars.

Chiarini and Kumar [15] discussed the integration between principles and tools of lean six sigma and industry 4.0 technologies. The data were collected through direct observations and interviewing manufacturing managers of ten Italian manufacturing companies. The result showed that Lean Six Sigma could achieve effective outcomes from industry 4.0 applications. However, the integration needs reinvented mapping tools and implies an end-to-end integration and vertical and horizontal integration. Saxby et al. [16] assessed how well lean management supports continuous improvement in industry 4.0. Semistructured interviews of five quality specialists in manufacturing were used to collect data and opinions for lean management and industry 4.0. The result showed that lean management could integrate new technologies for effectively continuous support in industry 4.0.

Ciano et al. [17] developed a framework on the relationship between industry 4.0 technologies and lean techniques. The developed framework focused on six areas: manufacturing equipment and processes, workforce management, shop floor management, customer relationship, supplier relationship, and new product development. The data were collected through semistructured interviews, internal documents, websites, and annual reports on lean and industry 4.0 implementation projects. Implemented the developed framework in eight sectors, and it has been revealed that as a result, industries' insights strongly believe that the industry 4.0 technologies could empower lean management techniques. Ghaythan et al. [18] examined the impact of the integration of lean manufacturing and industry 4.0 technologies on the sustainable performance of industries. The data required for the analysis were collected from questionnaires collected by 112 petrochemical and plastics industries. The analysis results showed that lean manufacturing and industry 4.0 have a positive impact on sustainability performance. Rossini et al. [19] investigated the impact of interrelation between the industry 4.0 technologies and lean production on the improvement level of operational performance in European manufacturers. The data has been collected by a survey conducted with 108 European manufacturers and analyzed through multivariate technique. The analysis identifies the interrelation according to different contextual factors, including lean production implementation experience, business operating model, type of ownership, and company size. The finding suggests that European manufacturers should apply concurrent lean production of industry 4.0 to achieve a high degree of process improvement.

However, only a few studies have been done on the methodology developed to identify an efficient process optimization technique for enhanced productivity within restricted resources. Here, constraints mean the availability of resources for shop floor management. To improve the process, it is necessary to get rid of the challenges and difficulties faced by the industry [20]. Typically, a production system is developed to identify the challenges and difficulties associated with production in the industry, which helps know where to get rid of the challenges and difficulties of production have to improve [21]. Through this system, information about the processes is collected so that the level of the processes can be evaluated and the production can be improved. The objective of the present article is to develop a smart production management system to identify the problems and challenges encountered on the production shop floor in industry 4.0 and suggest an efficient process optimization approach for industrial sustainability. The present article provides a systematic functional approach to provide a sustainable shop floor management system and to further enhance operational excellence within limited constraints. The proposed methodology has been described in Figure 2. There are five stages in the proposed methodology. The first stage focuses on layout draw and preparing a checklist of ergonomics issues by considering shop floor factors, including workplan, working environment, and workload distribution according to different departments. In the second stage, the production conditions are analyzed by calculating different parameters and resources condition by considering shop floor factors, including time, cost, worker, and shop floor congestion in various departments. The third stage reviews the machinery conditions and availability by observing and analyzing different departments and using advanced condition monitoring systems to improve machinery efficiency and utilization. In the fourth stage, the production shop floor planning is modified by brainstorming, meeting, conversations with production management teams, and using the internet of things, digitization, and data acquisition system. Finally, in the fifth stage, production shop floor improvement is validated by comparing proposed, observed, and previous results by considering product performance, approach, throughput, and shop floor management in different departments. As this methodology comprises nineteen different factors and each and every respective factor is crucial while implementing the same in various departments likes in inspection, quality, production, and design in industry 4.0, for example, the work plan sector is highly significant in the inspection department, quality department, and industry 4.0 department. The same other factors are very much prominent the same in the different departments that will provide a sustainable shop floor management system within available resources.

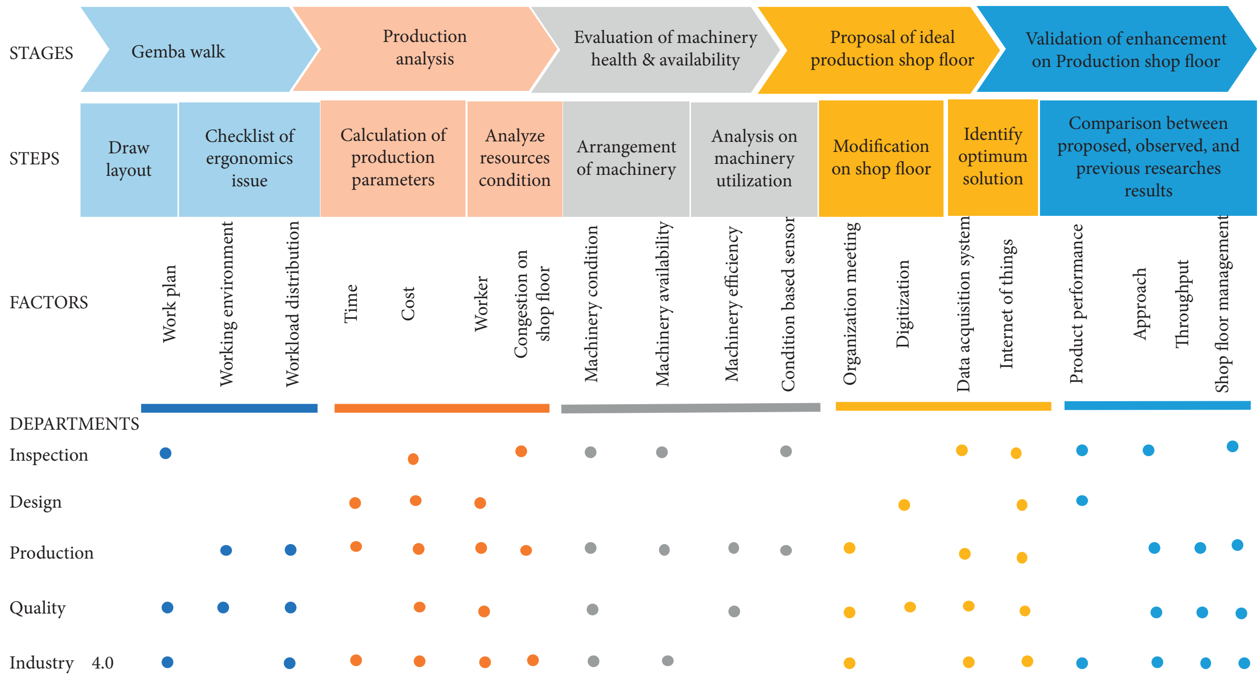


Figure 2: Proposed methodology.

2. Development of Novel Research Methodology

The literature review demands developing a research methodology to effectively implement the developed production management systems. The developed research framework helps implement the developed production management system and identification of NVAA so that appropriate action can be taken as per the production condition [22]. The present research methodology has been developed from a thorough analysis of factors of the production management system. Figure 3 illustrates the steps followed in the developed research methodology in the present research work.

The development of research methodology is a systematic way to implement process optimization methods that the elimination of waste in production can be possible. In previous researches, few researchers developed a methodology to improve the effectiveness of process optimization methods for shop floor management. In methodologies, emphasis was laid on determining the consumption of resources according to production and improving the production process. The following features distinguish the developed methodologies and prove to be important for the implementation of process optimization techniques.

(i) The developed methodology helps understand the reason of source of waste and investigated impact of working production processes on productivity in industry 4.0

(ii) The developed methodology provides a systemic illustration of material-flow, process-flow, time parameters (CT, LT, IT, and TT) to control the uncertainty in an advanced production environment

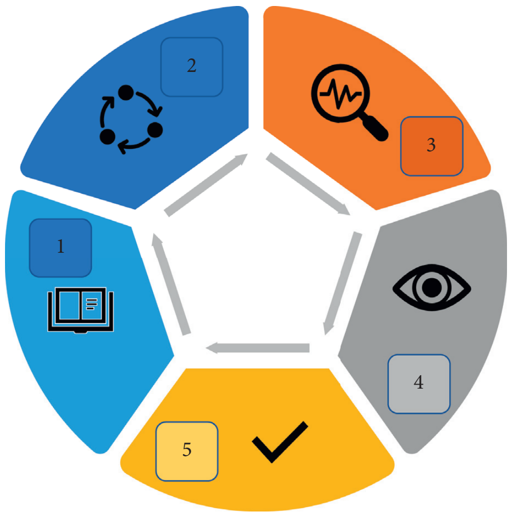
(iii) The developed methodology identifies problems and challenges by systematic analysis and helps provide an efficient action plan at beginning of production in industry 4.0

(iv) The developed methodology can be applied to any type of shop floor management in industry 4.0 and control overall process activities within available resources

3. Developments on the Process Optimization Approaches for Industrial Sustainability in Complex Environment

Researchers have proposed several methodologies of process optimization approaches for industrial sustainability in a complex environment. The complex environment includes discrepant working conditions, unexpected demand, over workload, lack of shop floor area, continuous working, and nonstandardization of work [23]. Process optimization concept originated from the Toyota production system and was developed by Taiichi Ohno's notion of "reduce time and cost by eliminating waste." Lean manufacturing, smart manufacturing, internet of things, and artificial intelligence are process optimization approaches and implemented for the elimination of waste. Waste means unnecessary activities performed in production that do not increase the product value [24]. Wastes have been classified into eight categories: overprocessing, overproduction, transportation, unnecessary motion, waiting, defects, and unutilized skill [25].

The process optimization approach is mostly preferred in industry 4.0 because it is capable of achieving production improvements with confined assets on automated production lines [26] and serves the purpose of process optimization while other techniques can be used in limited



1. Review of previous research work
   Discussion on previous research work on process optimization approach for production shop floor management.
2. Development of production management system
   Proposed a production management system to identify challenges and problems in industry 4.0
3. Deployment of proposed theory
   Implementation of developed theory in a case example of industry 4.0
4. Observation of production shop floor
   Observation of production processes and activities by gemba walk, virtual record, data acquisition system and discussion with industry persons.
5. Validation of developed system
   Industrial sustainability achieved in the production management, and comparative analysis between present and previous research work results.

Figure 3: Research methodology.

production conditions. Process optimization as an approach uses limited constraints that include the use of machinery, shop floor area, investment, production, process planning, and time [27]. The objective of process optimization is the minimization of waste in terms of time, manpower, machinery, and shop floor area. The concept of process optimization has been implemented by different techniques in industry 4.0; the techniques used in previous decades and in industry 4.0 are illustrated in Figure 4.

Lean manufacturing (LM) is a prevalent approach and has been used in most cases as found in the literature review. LM is used for the identification of NVAA by observation of shop floor conditions [28]. The cost incurred in these activities can neither be added to the production value nor paid by the customer [29]. Therefore, eliminating these activities from production is the only solution that is carried out by process optimization techniques [30]. It has been observed that LM is able to provide production enhancement in case of a manual assembly line, but if production line becomes semiautomated or fully automated, it does not work and the production management team must implement new techniques like integration of techniques.

In industry 4.0, production management team members emphasize on development of novel techniques and approaches for productivity enhancement in automated production lines. To accomplish this, several research works have been done in different automated production conditions, and smart manufacturing was found efficient in production management on the shop floor [31]. Smart manufacturing uses various techniques to the control management system in industry 4.0, including internet of things, digitalization, asset tracking system, artificial intelligence, and integration of smart manufacturing with other techniques such as lean, machine learning, and simulation. The complexity of the production situation has been increasing steadily over the past decade. Hence, in the current scenario of industry 4.0, more attention is paid to smart manufacturing techniques and hybrid approach with smart concept by the members of the management team. Because smart manufacturing has been found most suitable and efficient approach in productivity enhancement in previous research works.

As yet, several process optimization techniques have been implemented to improve the production on the shop floor [32]. An attempt has been made to tabulate all these techniques by Table 1 and presented a description of the application area and the results obtained. Figure 5 shows the techniques implemented in previous research for coping with problems and challenges. Table 2 illustrates the contribution of process optimization techniques in previous research works.

In research work over the past decades, authors have praised lean manufacturing for improving production, and other process optimization methods such as Kaizen and total quality management have also been used by some authors [22, 49, 71, 72, 85]. But it has been observed that smart manufacturing becomes the most preferred and prevalent approach in the past five years because of its higher adaptability in industry 4.0. This discussion of previous research endorses the utility of lean and smart manufacturing for process optimization. Researchers are skeptical about implementing procedures presented to address production challenges using lean and smart manufacturing, as the studies presented so far have proposed a specific approach and applied it only in confined situations. The authors of the present study are reviewing the methodologies presented in select previous studies to clarify the message. Following observations and research gap areas are identified:

(1) All the researchers that have developed the methodology of process optimization method applications in the manufacturing environment concluded that by improving the workflow on the shop floor, one can improve productivity and also concluded that this is not a generalized conclusion that can apply in all types of production conditions.

(2) There is no clarity in research on how to identify production challenges and problems in industry 4.0.

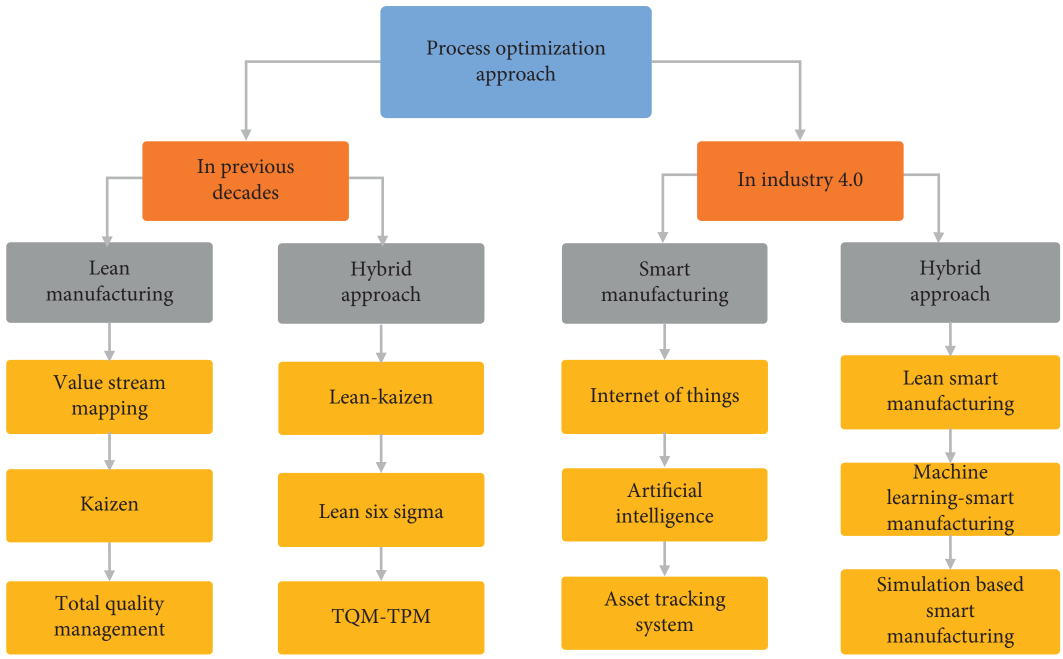


FIGURE 4: Process optimization techniques before Industry 4.0 (left) and under the framework of Industry 4.0 (right).

Therefore, the drawbacks of research to improve production through production mapping are clearly shown.

The objective of the present article is to develop a smart production management system to identify the problems and challenges encountered on the production shop floor in industry 4.0 and suggest an efficient process optimization approach for industrial sustainability. The research objective raised questions for the study are as follows:

(i) How to demonstrate the key message of process optimization through an efficient technique using a methodology for reducing wastes influencing productivity in industry 4.0

(ii) How to identify wastes in the industry 4.0 production environment by applying the proposed production management system

4. Scientific Gap in the Literature and Conceptual Paradigm Objectives of the Current Research Work

In industry 4.0, the production team members face several problems in enhancing operational excellence due to complexity in the shop floor environment [92]. It has been observed that if production teams ignore different circumstances and issues that can be developed by complexity in the shop floor environment, it results in considerable losses in financial profitability [93]. A comprehensive review of the production management systems developed in previous research has been found that the developed systems were not efficient at controlling operational excellence in all types of shop floor environments and could only increase productivity in certain limited production conditions. Therefore, the production management teams emphasize developing an intelligent system to eliminate the problems faced in different circumstances because of the complex shop floor environment [94].

The developed system helps provide a guideline for selecting a suitable approach for enhancing industrial sustainability in industry 4.0. The proposed smart system has been developed by various brainstorming sessions on problems and challenges faced in production shop floor management, including industry 4.0. The developed system provides a guideline for management teams to understand the actual shop floor conditions and help make an action plan at the beginning of production processes to achieve industrial sustainability enhancement. The developed smart production management system has been validated by enhancing industrial sustainability in the case of industry 4.0. It has been found that the developed system provided improvement in production time, worker's contribution, machinery utilization, operational excellence, and financial profitability by 17%, 18%, 28%, 35%, and 45%, respectively.

The present research aims to develop a smart production management system to identify the problems and challenges encountered in production on the shop floor in industry 4.0 and suggest an efficient process optimization approach for industrial sustainability. The developed smart management system can improve operational excellence in any complex shop floor environment within confined assets and the efficient to enhance sustainability in all industries, including automobile, mining machinery, mining, defense, aerospace, pharmaceutical, chemical, and so on. The authors of the present research article that the developed system would be preferred in shop floor management in industry 4.0 because it can implement a suitable approach by identifying exact problems in

Table 1: Description of previous research work, technique, and results.

Author(s)	Year	Techniques	Results: Improvement/reduction	Results: Optimized resources
Östlin and Ekholm [33]	2007	Value stream mapping (VSM)	Setup time	Manpower
Seth and Gupta [34]	2007	VSM, Kanban	WIP (work in process), inventory, production lead time (LT), processing time	Cost
Gati-Wechsler and Torres [35]	2008	TPM, 5S, JIT, Kanban	Inventory	NA
Sahoo et al. [36]	2008	VSM, Taguchi's method	Setup time, WIP inventory level, defect	NA
Pattanaik and Sharma [37]	2009	Cellular manufacturing system, VSM	Lead time (LT), setup time, waiting time, material handling time	Layout
Singh Sharma [38]	2009	VSM	LT, processing time, WIP	Manpower
Vinodh et al. [39]	2010	VSM	Cycle time (CT), idle time (IT), WIP inventory, defect, uptime (UT)	Manpower
Rahman and Al-Ashraf [40]	2012	VSM	Production LT, work-in-process inventory	Manpower, machine, layout
Rahman et al. [41]	2012	Kanban	Inventory	Cost
Chen et al. [42]	2013	VSM, radiofrequency identification	LT, waiting time	Shop floor area
Bertolini [43]	2013	VSM	Productivity, LT, defect	Cost
Longhan et al. [44]	2013	VSM	Productivity	Cost
Jeyraj et al. [45]	2013	VSM	Takt time (TT), LT	Machine, manpower
Das et al. [46]	2014	VSM, SMED, Kaizen	Setup time, WIP inventory	Shop floor area
Barbosa et al. [47]	2014	LM, TPM	Cycle time (CT), product quality	Layout
Kumar et al. [48]	2014	VSM, method study	LT	Layout
Ismail et al. [49]	2014	Lean Six Sigma, VSM	CT	NA
Singh et al. [50]	2014	LM	Cycle time, downtime	Cost
Santos et al. [51]	2015	5S, VSM, Kaizen,	Productivity	Manpower
Mwanza and Mbohwa [52]	2015	Total productive maintenance	Downtime	Machinery
Choi et al. [53]	2015	Smart manufacturing	Production enhancement	Cost
Rohani and Zahree [54]	2015	VSM, kaizen, Kanban, 5S	LT	NA
Esa et al. [55]	2015	SMED	Setup time	Manpower
Lu and Yang [56]	2015	VSM, Kaizen	Production, CT	Manpower
Tyagi et al. [57]	2015	VSM, Gemba walk	LT, quality	Cost
Choomlucksana et al. [58]	2015	Kaizen, 5S, poka-yoke	Processing time	Cost
Naqvi et al. [59]	2016	LM, Kaizen, 5S	LT, production	Layout, cost
Andrade et al. [60]	2016	VSM	LT, production time	Manpower
Thomas et al. [61]	2016	Lean Six Sigma	Production time	Cost
Garre et al. [62]	2017	5S, SMED	Productivity, total cycle time (TCT)	Layout
Asif and Singh [63]	2017	Internet of things	Productivity	Cost
Dadashnejad and Valmohammadi [64]	2017	VSM, overall equipment effectiveness	Productivity, quality	Machine
Diaz et al. [65]	2017	VSM	LT, CT, quality	Manpower
Méndez and Rodriguez [66]	2017	TPM, overall equipment effectiveness	Productivity	Manpower
Nagadi et al. [67]	2017	Smart manufacturing	Production time	Machinery
Gazra-Reyes et al. [68]	2018	VSM, TPM, just in time, Kaizen	Productivity, quality	Energy consumption
Gijo et al. [69]	2018	Lean Six Sigma	Defect	Cost
Stadnicka and Litwin [70]	2018	VSM, system dynamic analysis	Work-in-progress	Machine
Cannas et al. [71]	2018	Kaizen, Yamazumi chart, standardization	Performance	NA
Kumar et al. [72]	2018	VSM, Kaizen, poka-yoke, 5-why, brainstorming technique	Lead time, cycle time, inventory level, productivity, quality, rework elimination	Machine, manpower, cost

Table 1: Continued.

Author(s)	Year	Techniques	Results	
			Improvement/reduction	Optimized resources
Suhardi et al. [73]	2019	VSM, 5W1H (what, who, where, when, how, why), ECRS (eliminate, combine, rearrange, and simplify) principle	Lead time	Manpower
Saqlain et al. [74]	2019	Internet of things	Production time	Machinery, cost
Masuti and Dabede [75]	2019	VSM	Cycle time, lead time	Cost
Ramani and Lingan [76]	2019	VSM	Productivity	Cost
Priya et al. [77]	2019	Lean Six Sigma, just in time	Defect, quality	NA
Liao and Wang [78]	2019	Internet of things	Production time	Cost
Shou et al. [79]	2019	VSM	Production time	NA
Sharma et al. [80]	2019	5S	Productivity	Machine, cost, shop floor
Abubakr et al. [81]	2020	Smart manufacturing	Productivity	Machinery, cost
Torres et al. [82]	2020	Smart manufacturing	Production time	Cost, shop floor
Prasad et al. [83]	2020	VSM, 5S, Kaizen, Kanban, SMED	Productivity	Layout
Mittal et al. [84]	2020	Smart manufacturing	Production	Cost
Balamurugan et al. [85]	2020	Cause and effect diagram, failure mode effect analysis	Productivity	Machine, shop floor
Chien and Chen [86]	2020	Smart manufacturing	Production time	Machinery, cost
Amrani and Ducq [87]	2020	VSM, SMED, cellular layout	Setup time, cycle time, defect rate	Cost, manpower
Frankó et al. [88]	2020	Internet of things	Production time	Machinery, cost
Gaspar et al. [89]	2021	Internet of things	Production time	Cost
Reyes et al. [90]	2021	Lean and industry 4.0 technologies	Productivity	Cost
Vlachos et al. [91]	2021	Lean and internet of things	Productivity	Cost

the complex production environment. Figure 6 shows the current model of shop floor management that was being used by the production management team.

5. Proposed Production Management System

Industries face several challenges and problems in controlling the shop floor management. Therefore, to identify these problems and challenges, a smart production management system has been developed in the present research. In the production management system, the challenges and problems are classified in observed forms. The developed production management system has been evaluated by problems found in prior research and applied techniques. Table 3 classifies the challenges commonly encountered by industry in production and the problems associated with them.

Most of the researchers appreciated lean and smart manufacturing and acknowledged problems and challenges complexities in an industrial environment. Authors mostly suggested lean for improvement in production and shop floor management in the last decades. The smart manufacturing experience of researchers in production improvement is remarkably diverse and endorsed the reliability of smart manufacturing in shop floor management.

To get rid of the challenges and problems faced at the production shop floor, in the current research work, an extensive literature review was done on the work done in the production area and industry 4.0, and a production management system has been developed. The challenges and problems were categorized to prepare the developed system and the process optimization techniques applied in the previous research were brainstormed for them. A management system has been developed from the findings obtained from the brainstorming analysis. The authors are strongly believed that the developed production management system would be capable of providing higher throughput in all types of conditions in industry 4.0. The developed smart production management system has been illustrated in Figure 7. The proposed smart production management system follows four steps and is developed by multiple brainstorming sessions organized at the different department levels and using previous research works.

5.1. Experimentation of Proposed Theory in a Case Study for Industry 4.0. The present study has been carried out in an earthmoving machinery manufacturing unit in India. The industry currently has 52 people including managers, supervisors, and employees and operates in a single shift with 10 working hours. The present industry manufactures several types of machinery such as the skid-steer loader, cranes, and truck-mounted. This research work deals with skid-steer loader production processes. Skid-steer loader is an earthmoving machinery, and it is based on cutting-edge technology. The industry is facing stiff competition due to high manufacturing cycle time. Typically, production orders are received intermittently and mostly in small quantities.

The production lead time and quality are the main factors to face the competition of the industry. When the industry is faced with problems such as high costs and excessive lead time due to wastage, the level of production becomes exceedingly difficult to control. Production management is therefore vigilant about these problems and

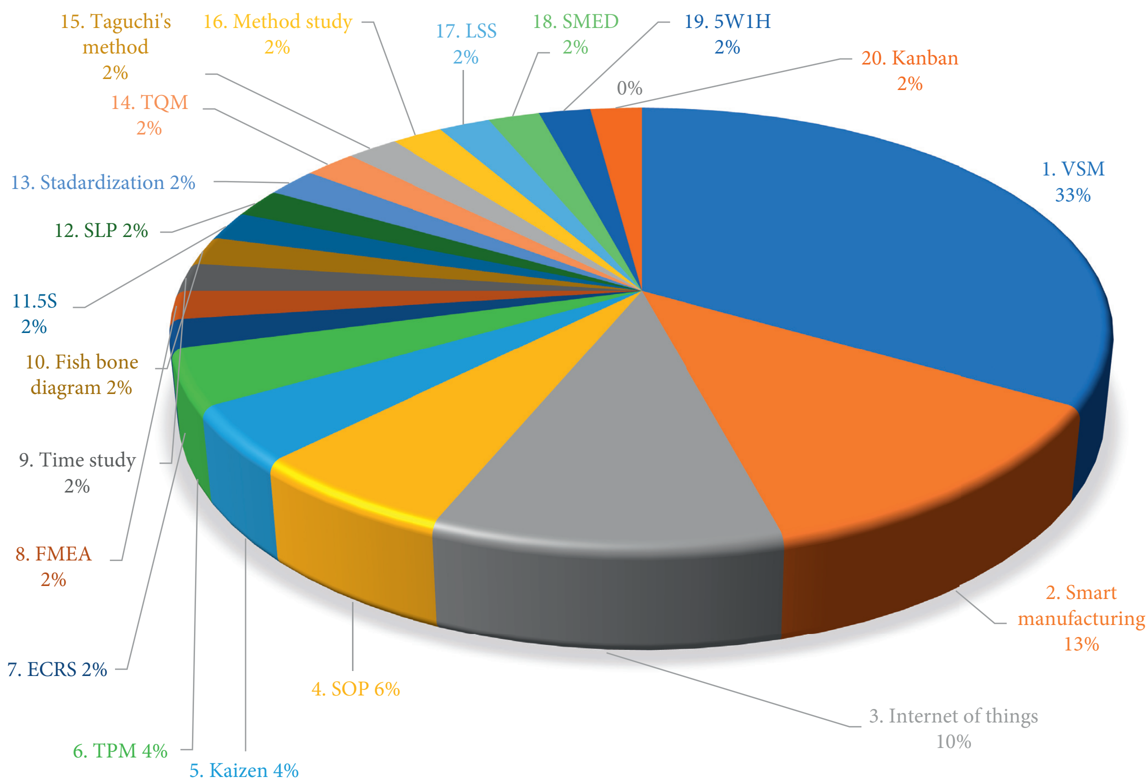


Figure 5: Implementation of process optimization techniques in previous researches.

Table 2: Contribution of process optimization techniques in previous research works.

S. No.	Process optimization techniques	Contribution (%)
1	VSM	33
2	Smart manufacturing	13
3	Internet of things	10
4	SOP	6
5	Kaizen	4
6	TPM	4
7	ECRS	2
8	FMEA	2
9	Time study	2
10	Fish bone diagram	2
11	5S	2
12	SLP	2
13	Standardization	2
14	TQM	2
15	Taguchi's method	2
16	Method study	2
17	LSS	2
18	SMED	2
19	5W1H	2
20	Kanban	2

emphasizes the implementation of process optimization methods for production on the shop floor. The problems found in controlling production in the current industry are illustrated by Figure 8.

5.2. Observation of the Production Shop Floor in Present Case Report. According to Womack and Jones [95], production planning plays an important role in achieving customer needs in the context of the product. For this, it is necessary to observe the precise production information and conditions of the industry. So those necessary arrangements can be made to deal with them. The basic production information has been collected by observation of shop floor, questionnaire, data acquisition system, interviews, and discussion with industry persons. The observation of the shop floor has

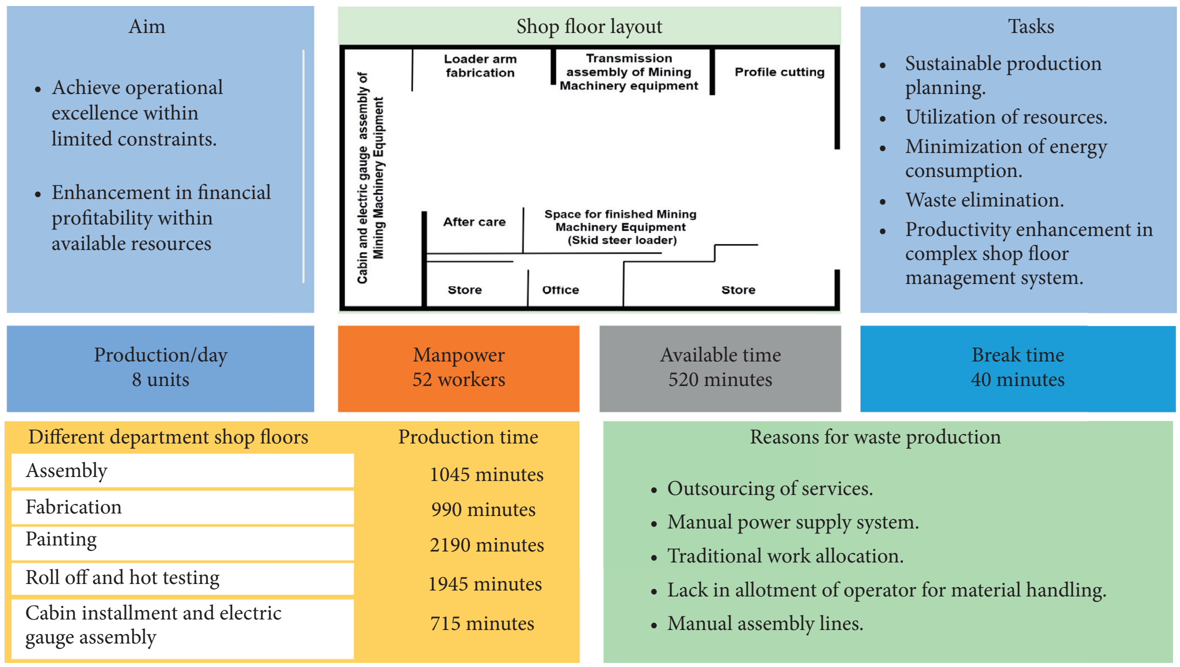


Figure 6: Current shop floor management model.

Table 3: Categorization of problems and challenges faced in production.

S. No.	Challenges	Problems	Categorization	Author and reference number	Implemented shop floor management technique
1	Productivity	Poor layout	P_1	Rahman and Al-Ashraf [40]; Saqlain et al. [74]	VSM, smart manufacturing
		Absenteeism	P_2	Singh and Sharma [38]	VSM, 5S
		Higher downtime	P_3	Santos et al. [51]; Chien and Chen [86]	VSM, smart manufacturing
		Unskilled worker	P_4	Jeyaraj et al. [45]	VSM
		Communication gap	P_5	Esa et al. [55]	Standard operating procedure (SOP)
		More workstation	P_6	Rohani and Zahree [54]	VSM, Kaizen
		Work overloaded	P_7	Garee et al. [62]	Single minute exchange of die (SMED)
		High setup time	P_8	Esa et al. [55]	SMED
2	Quality	Lack in worker sill	Q_1	Seth and Gupta [34]	VSM
		Lack of standard	Q_2	Rahman and Al-Ashraf [40]; Asif and Singh [63]	SOP, internet of things
		Defect	Q_3	Pattanaik and Sharma [37]	VSM
		Workload distribution	Q_4	Suhardi et al. [73]	5W1H technique, ECRS principle
		Inventory	Q_5	Masuti and Dabede [75]	VSM
3	Time	Lack in production planning	T_1	Balamurugan et al. [85]; Priya et al. [77]; Gaspar et al. [89]	Time study, fishbone diagram, failure mode effect analysis (FMEA), internet of things
		Downtime	T_2	Barbosa et al. [47]	Total productive maintenance
		Machinery utilization	T_3	Jeyaraj et al. [45]	VSM
		Wrong workload distribution	T_4	Chen et al. [42]	VSM
		Unsystematic layout	T_5	Ali Naqvi et al. [59]	Systematic layout planning
		Absentees	T_6	Amrani and Ducq [87]	Standardization
		Unskilled worker	T_7	Gati-Wechsler and Torres [35]	Total quality management (TQM)
		Communication gap	T_8	Esa et al. [55]	SOP
		Lack in material handling	T_9	Frankó et al. [88]	Asset tracking system

Table 3: Continued.

S. No.	Challenges	Problems	Categorization	Author and reference number	Implemented shop floor management technique
4	Cost	Downtime	C_1	Mwanza and Mbohwa [52]; Chien and Chen [86]	Total productive maintenance (TPM), smart manufacturing
		Lack in worker participation	C_2	Rahman et al. [41]	Lean manufacturing, Kanban
		Defects	C_3	Sahoo et al. [36]	Taguchi's method
		Inventory	C_4	Singh and Sharma [38]	VSM
		Unplanned workflow	C_5	Kumar et al. [72]; Ramani and Lingan [76]; Liao and Wang [78]	VSM, method study, internet of things
5	Customer satisfaction level in terms of product	Higher lead time	L_1	Östlin and Ekholm [33]; Liao and Wang [78]	VSM, internet of things
		Defects	L_2	Bertoloini [43]	VSM
		Standard	L_3	Ismail et al. [49]; Gijo et al. [69]	Lean Six Sigma
		Quantity	L_4	Longhan et al. [44]	VSM
		Design	L_5	Das et al. [46]; Mittal et al. [84]	VSM, SMED, Kaizen, smart manufacturing

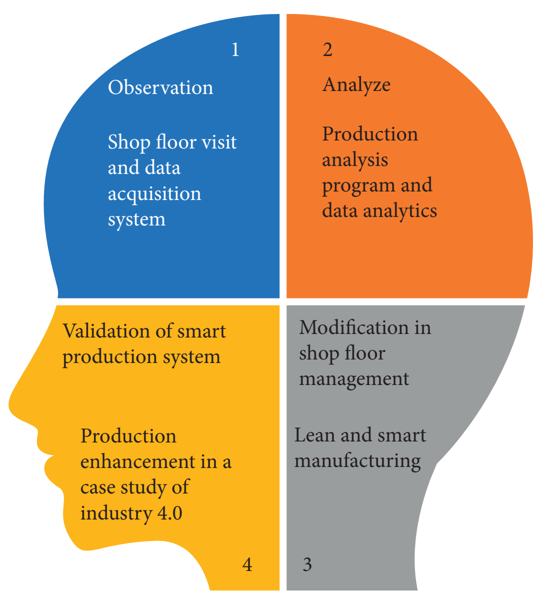


Figure 7: Proposed smart management system for industry sustainability in industry 4.0.

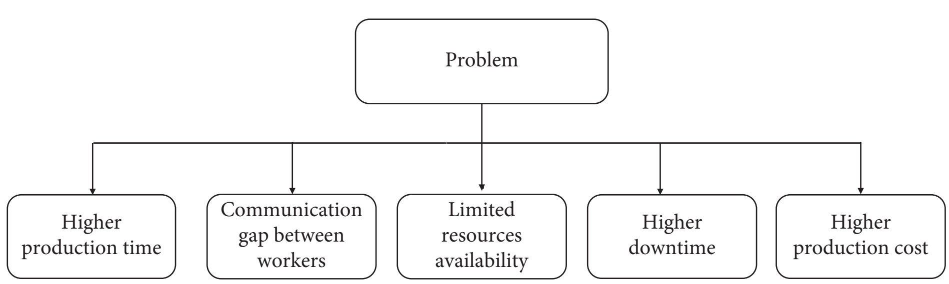


Figure 8: Observed problems of present industry.

been used to understand the working condition of production on the shop floor. The discussion with workers, supervisors, and managers has been used for the analysis of production information and shown by Table 4.

5.3. Analyze Present Production Shop Floor Management. The working condition map of production processes is shown in Figure 9. The working map demonstrates that the manufacturing orders are being received monthly and the

Table 4: Details of production collected from the observation of the shop floor.

Name of data	Quantity
Product name	Skid steer loader
Working time	560 minutes
Break time	40 minutes
Available time	520 minutes
Number of workers	52
Number of processes	18
Number of shifts	1
Number of shops	5
Production per day (PD)	8
Shop floor area	34 meter × 75 meter
Production line	Semiautomated
Production type	Pull
Material handling equipment	Hoist for material handling and forklift
Challenge	Productivity, time, quality, customer satisfaction level
Previous production record	WT: 580 minutes, BT: 80 minutes, PD: 9 minutes
Problems	P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, T_9, L_1, L_4
Working environment	Unfriendly due to more working hours and unplanned work
Working temperature	Workable
Maintenance type	Preventive
Outsourcing services	Painting (chassis and loader arm)
Number of components in the final product	Approximate 800
Implemented shop floor management technique	5 S

shop floor management department transmits the manufacturing instructions on daily basis to the supervisor and workers. In present production condition, a total of 18 processes are performed in the production of the skid steer loader, and the industry operates in one shift per day. The total cycle time (TCT) for manufacturing the skid-steer loader is 6,540 minutes whereas the total idle time (TIT) is 470 minutes. The skid-steer loaders are manufactured to the customers' demands mostly monthly. The industry normally maintains a product inventory of 15 units due to uncertainty in employee availability.

In the observed condition, the proposed production management system has been used to identify production problems and elimination of non-value-added activities. For the elimination of problems, the appropriate technique has been selected from the process optimization techniques implemented in the previous research work, as shown in Table 2. Table 5 shows the description of problems and challenges identified in production processes.

The production analysis program and data analytics were implemented for the identification of problems and non-value-added activities so that they could be eliminated with the appropriate action. Lean and smart manufacturing were found suitable to improve mostly processes, and additionally, internet of things, artificial intelligence, and embedded system have been applied in some other processes.

6. Result and Discussions

6.1. Development of a Modified Production Shop Floor Management. After the analysis of NVAA present in the production processes of skid-steer loader, various proposals for NVAA elimination have been developed by a discussion with the workers of industry, which are presented as follows:

(i) Improvement in shop floor management – The principle of lean smart manufacturing has been found effective for implementation at the following processes, namely wheel assembly, chassis manufacturing, cabin installment, and electric gauges assembly

(ii) Reduction of a number of workstations – The production planning at workstations has been improved by simulation and machine learning concepts

(iii) Reduction of work-in-progress–The unnecessary activities between production processes has been eliminated by the lean concept

(iv) Improvement in resource utilization – The utilization of machinery and workers has been improved by using artificial intelligence and the internet of things concept

(v) Reduction of high setup time – The internal activities (preparing setup jig and fixture, movement of chassis component, material handling of components by forklift and hoisting equipment, transportation of large parts for painting, and changing attachment tool) have been considered as external activities

(vi) Improvement in the communication gap between workers-organized meeting and conducting the training program

Table 6 shows the overall production modification suggested for proposed planning. The proposed modified production planning describing the various improvements incorporated in the production processes of the skid steer loader on the shop floor is shown in Figure 10.

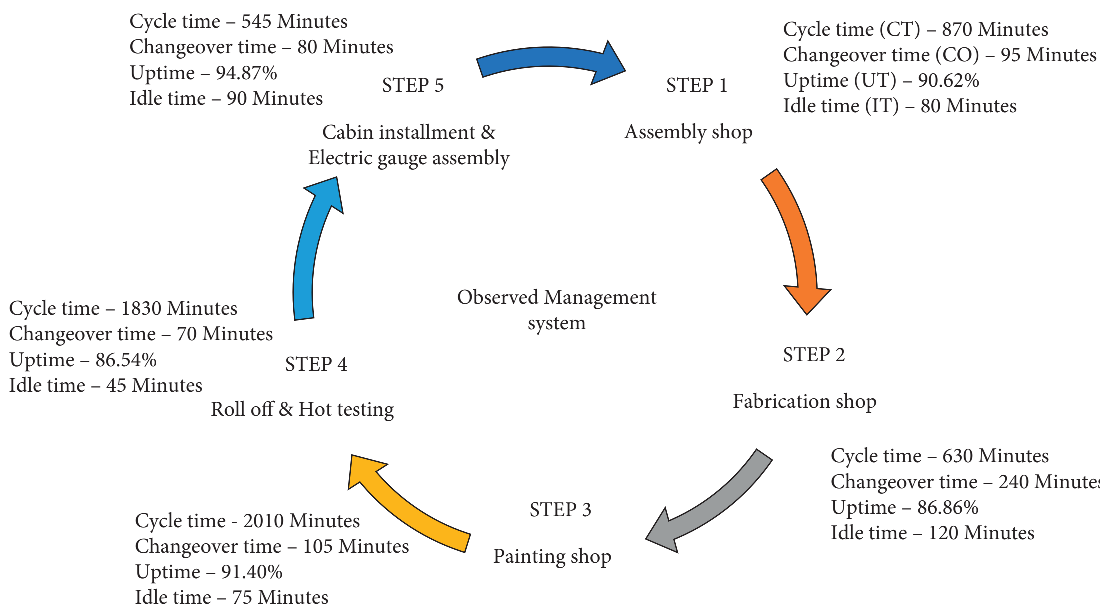


FIGURE 9: Observed production management condition.

TABLE 5: Challenges and problems identified in production processes.

S. No.	Process	Problem
1	Transmission assembly	$P_1, P_2, P_4, P_5, P_6, P_7, P_8, T_1, T_2, T_4, T_5, T_6, T_7, T_8, T_9, L_1$
2	Manufacturing of loader arm	$P_4, P_5, P_6, P_8, T_1, T_3, T_4, T_7, C_2, L_1$
3	Chassis manufacturing	$P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, L_1, L_4$
4	Wheel assembly	P_5, T_8
5	Chassis and loader arm fabrication	$P_1, P_3, P_4, P_5, P_8, T_3, T_7, T_9L_1$
6	Inspection of fabrication	$P_2, P_3, P_5, T_1, T_2, T_3, T_8$
7	Painting (baby parts)	P_8
8	Painting (large parts)	P_8
9	Engine assembly	$P_1, P_7, P_8, T_3, T_4, T_5, T_8, L_1$
10	Hydraulic pump and motor assembly	$P_1, P_7, P_8, T_3, T_4, T_5, T_8, L_1$
11	Inspection of assembly and roll off	T_1
12	Hot testing	$P_3, P_5, P_7, P_8, T_1, T_4, L_1$
13	Cabin installment	$P_4, P_5, P_7, T_1, T_4, T_7, T_8$
14	Electric gauges assembly	$P_4, P_5, P_7, Q_1, Q_4, T_1, T_4, T_7, T_8$
15	Final inspection	$P_1, P_5, P_6, P_7, T_1, T_4, T_8$

A similar work has been reported by Müller et al. [96] who discussed how natural language processing could improve the digital shop floor management concept to provide higher value for decision-makers and the shop-floor teams. The study presented a conceptual approach by integrating the fields of natural language processing and digital shop floor management to discuss assistant functions in digital shop floor management on the text data produced during problem-solving. The result of the study revealed that the developed approach was detailed, quick, and accurate by representing an actual condition in the company. Xu et al. [97] investigated the coexistence of two industrial revolution industry 4.0 and industry 5.0. In the study, five questions were selected by different sources, and the questions were rooted in industry and the scientific community. The study showed that the industrial revolution was driven by transformative technological advances that helped improve fundamental changes in the industry functions. These fundamental changes included social and economic consequences. It also concluded that the revolution upgrade had been required technological pushes and solutions. Mourtzis [98] discussed the benchmarking obtained in the evolution of manufacturing systems simulation technologies and investigated recent research and industrial revolution in the fields of manufacturing. The study showed that digitalization provides data and new technologies to assist in manufacturing simulation and product design in the new era.

6.2. Validation of Proposed Smart Production Management System. Present research methodology demonstrates its usefulness in terms of improved productivity, customer satisfaction level, resources utilization, and production time.

Table 6: Details of proposed production planning from the investigation of the production shop floor.

Name of data	Quantity
Product name	Skid-steer loader
Working time (WT)	600 minutes
Break time (BT)	90 minutes
Available time	510 minutes
Number of workers	52
Number of processes	10
Number of shifts	1
Number of shops	5
Production per day	12
Shop floor area	34 meter × 75 meter
Material handling equipment	Hoist for material handling and forklift
Challenge	Productivity, time, customer satisfaction level
Previous production record	WT – 520 minutes, BT – 40 minutes, PD – 8
Problems	Eliminated
Working environment	Aesthetic
Maintenance type	Condition-based maintenance
Outsourcing services	Painting (chassis and loader arm)
Number of components in the final product	Approximate 800
Implemented shop floor management approach	Lean smart manufacturing, internet of things, artificial intelligence, asset tracking system

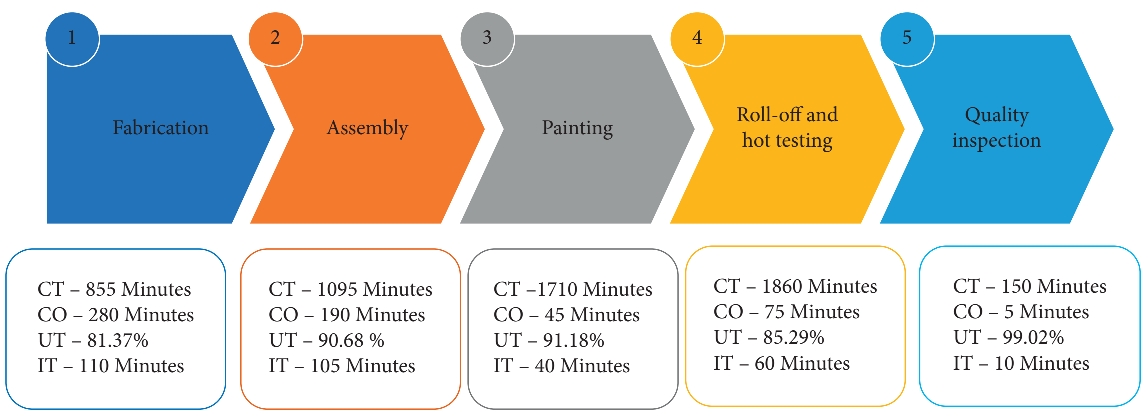
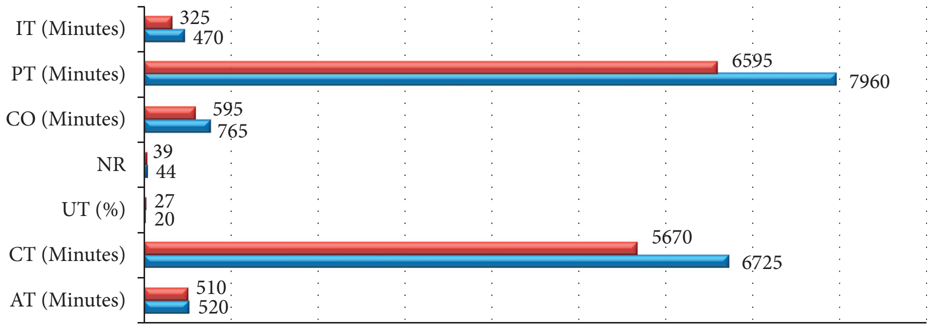


Figure 10: Modified production management system.

The case study revealed that the proposed production management system can provide precise identification of the challenges and problems responsible for production in industry 4.0 using a lean and smart manufacturing approach. The production management helps the management system implement a suitable shop floor management approach for the elimination of non-value-added activities. To validate the production management system presented, it was implemented in a production condition of industry 4.0, and it was found that production improved as per the standards set by the production management system. Production improvement has been calculated according to various parameters. These improvements are shown in Figure 11.

In line with the problems encountered in shop floor management, the present case example shows the elimination of non-value-added activities and the improvement in productivity levels that have been possible through the proposed smart production management system. To substantiate this statement, a comparative analysis was carried out from the present work from previous research work. It was found that the proposed production management system is better in eradicating of all production problems and non-value-added activities. The comparative analysis between some relevant previous research and the present study has shown in Table 7.

The related work has been reported by Mourtzis [99] designed a model of a real manufacturing system using discrete-event simulation and evaluated it by obtaining actual data obtaining from the copper industry. The study used the ANOVA method to highlight the effect of each decision variable on the model. The study demonstrated that the manufacturing system could obtain maximum throughput by utilizing actual data and available resources. Mourtzis [100] developed a framework for remote monitoring refrigerator and cold storage systems using wireless sensor networks and cloud technology for predictive maintenance. In the study, wireless sensor networks and the intelligent algorithm were integrated for predictive maintenance. The study showed that the developed framework could provide yielded promising results. Mourtzis [101] discussed the latest advances and challenges of machine tool evolution in the present industrial era in the manufacturing



	AT (Minutes)	CT (Minutes)	UT (%)	NR	CO (Minutes)	PT (Minutes)	IT (Minutes)
Modified	510	5670	27	39	595	6595	325
Observed	520	6725	20	44	765	7960	470

FIGURE 11: Production improvement by the presented production management system.

TABLE 7: Comparison between previous results and present study investigation.

Author's	Technique	Improvement (%) PT	CT	Defect	Parameter	Optimized
Cinar et al. [20]	VSM	1.11	2.59	4	Production time, machinery utilization, quality	Machinery, cost
Liao and Wang [78]	Internet of things	NA	NA	NA	Product quality	Cost
Rahani and Al-Ashraf [40]	SMED, poka-yoke, standardization	NA	43	66	Production time, product quality	Cost
Chien and Chen [86]	Smart manufacturing	NA	NA	NA	Production time	Machinery
Ismail et al. [49]	LSS	16.79	NA	NA	Production time	Cost
Gijo et al. [69]	LSS	NA	NA	85.26	Quality	Cost
Asif and Singh [63]	Internet of things	NA	NA	NA	Production management	Cost
Das et al. [46]	VSM, SMED, kaizen	57.07	43.24	NA	Production time	Cost
Frankó et al. [88]	Internet of things	NA	NA	NA	Logistic task	Machinery, cost
Longhan et al. [44]	VSM	6.85	NA	NA	Production time	Cost
Choomlucksana et al. [58]	VSM	8.02	37.05	NA	Production time	Cost
Present study	Lean and smart manufacturing, internet of things, VSM	17.14	15.69	42	Production time, machinery and manpower utilization, quality	Manpower, machinery, cost, shop floor

domain. In addition, the study recognized emerging opportunities and identified implications from the implementation point of view.

6.3. Enhancement of Industrial Sustainability of the Developed Methodology for Industry 4.0 for Earthmoving Machinery Manufacturing Shop Floor Management System. The present research methodology can be applied to improve all types of earthmoving machinery manufacturing conditions in industry 4.0. This statement has been proved by an example: this example was of an earthmoving machinery manufacturing unit, in which production was improved by the implementation of the developed production management system in industry 4.0. The improvements obtained in the operational performance of production processes by process optimization techniques are shown in Table 8. The planning and execution of research methods in the manufacturing unit, and improvement in shop floor management has summarized in Table 9.

Productivity enhancement has been achieved effectively by the production management system developed in the present case study. The implementation of the developed methodology led to an improvement of up to 35% in the production by a 42% reduction in defects by the implementation of a suitable process optimization approach. The result of the study validates the author's statement about developed methodology and describes that the developed production management system would provide industrial sustainability in industry 4.0. The related work has been reported by Liu et al. [102] investigated the emerging industrial internet of things implementation in a cloud manufacturing system for addressed the challenge faced in the development of cloud manufacturing systems. The challenges included communication, efficient data acquisition, analysis of field-level manufacturing equipment, and query. Two industrial internets of things gateway for a 3D printer and a CNC machine tool validated the approach. The result showed that integrating various emerging industrial internet of things technologies in manufacturing systems

Table 8: Improvements in the parameters of production processes.

S. No.	Process	Process (modified)	Reduction (available time) minute	Improvement (uptime) %	Improvement (number of operators)	Improvement (changeover time) minute	Improvement (cycle time) minute	Improvement (production time) minute	Improvement (idle time) minute
1	Transmission assembly	Transmission assembly	10	0.56	1 (Increase)	5	45	60	10
2	Manufacturing of loader arm	Manufacturing of loader arm	10	2.72	1 (Increase)	15	15	35	5
3	Chassis manufacturing	Chassis manufacturing	10	0.62	1 (Increase)	5	15	40	20
4	Wheel assembly	Wheel assembly	10	0.88	1 (Increase)	5	25	30	0
5	Chassis and loader arm fabrication	Chassis and loader arm fabrication	10	2.34	2 (Reduce)	0	30	45	20
6	Inspection of fabrication								
7	Painting (baby parts)		10	10.53	1 (Decrease)	60		395	35
8	Painting (large parts)	Painting					300		
9	Engine assembly				1 (Increase)			90	
10	Hydraulic pump and motor assembly	Assembly (engine, hydraulic pump and motor)	10	7.16		40	35		15
11	Quality inspection and roll off	Quality inspection, roll off, and hot testing	10	1.24	0		525	545	10
12	Hot testing					10			
13	Cabin installment	Cabin installment and electric gauges assembly	10	3.29	2 (Reduce)	20	55	100	25
14	Electric gauges assembly								
15	Final inspection		10	1.9	0	10	10	25	5

Table 9: Implemented actions for improvement in production on the shop floor.

S. No.	Process	Cause of problem	Process optimization approach	Suggested action	Improvement in process time (%)
1	Transmission assembly	(i) There was no fixed place for different assembly processes (ii) Gearbox assembly has done at a different location (iii) Unnecessary transportation due to different locations of processes (iv) Lack of workers (v) Poor planning	Lean smart manufacturing	(i) All assembly processes were performed in one shop that also included gearbox assembly (ii) Prepared a systematic layout (iii) Increased number of workers (iv) Improved shop floor planning (v) Automated production line (vi) Asset tracking system	11.32
2	Manufacturing of loader arm	(i) Higher setup time (ii) Lack of workers (iii) Unawareness of the work (iv) Lack of action plan	Lean manufacturing	(i) Increased number of workers (ii) Organized meeting and training (iii) Improved action plan	9.21
3	Chassis manufacturing	(i) Manual material handling (ii) Unsystematic planning (iii) No sequence of production processes was determined (iv) Lack in worker skill	Value stream mapping and internet of things	(i) Prepared a systematic planning (ii) Organized appropriate training program (iii) Digitalization	9.19
4	Wheel assembly	(i) Unawareness of the worker	Embedded system	(i) Organized meeting (ii) Prepare to code for operations	15.78
5	Chassis and loader arm fabrication	(i) A Longer distance between chassis and loader arm shop (ii) Higher setup time	Smart manufacturing	(i) Both the shops were set up side by side in the revised layout (ii) Increased number of workers (iii) Dynamic modeling of shop floor (iv) Digitalization	8.108
6	Inspection of fabrication	(i) Higher setup time (ii) Unnecessary transportation for the inspection process (iii) No fixed location was decided for inspection	Internet of things, artificial intelligence	(i) Inspection has done at previous workstation (ii) Inspection has done just after completion of fabrication of loader arm and chassis (iii) Program for standard specification of product	
7	Painting (baby parts)	(i) Lack of worker	Embedded system	(i) Increase worker (ii) Automated production line	18.03
8	Painting (large parts)	(i) Lack of worker (ii) Painting of large parts from other industry	Lean manufacturing	(i) Increase worker (ii) Both painting processes were started out simultaneously	

Table 9: Continued.

S. No.	Process	Cause of problem	Process optimization approach	Suggested action	Improvement in process time (%)
9	Engine assembly	(i) Lack of worker (ii) Poor planning (iii) Unawareness of the worker	Lean smart manufacturing	(i) Increase worker (ii) Improved planning (iii) Organized meeting (iv) Simulation and modeling of workstation (v) Digitalization	21.17
10	Hydraulic pump and motor assembly	(i) Lack of worker (ii) Unsystematic layout (iii) Unawareness of the work	Smart manufacturing	(i) Increase worker (ii) Modified layout (iii) Organized meeting (iv) Automated production line (v) Digitalization	
11	Quality inspection and roll off	(i) Lack in production planning (ii) Unnecessary documentations	Artificial intelligence	(i) Improved production planning (ii) Prepare a coding-based specifications (iii) Digitalization	21.46
12	Hot testing	(i) Lack of worker (ii) No time limit decided (iii) Drawback in planning	Embedded system	(i) Increase worker (ii) Decided a time limit for processes (iii) Improved planning	
13	Cabin installment	(i) Unsystematic layout (ii) Unawareness of the work (iii) Lack in shop floor planning	Lean smart manufacturing	(i) Improvement in layout (ii) Organized meeting and training (iii) Improved shop floor planning (iv) Embedded system	19.05
14	Electric gauges assembly	(ii) Unsystematic layout (ii) Unawareness of the work (iii) Lack in shop floor planning (iv) Unnecessary movement	Lean smart manufacturing	(i) Improvement in layout (ii) Organized meeting and training (iii) Improved shop floor planning (iv) Cabin installment and electric gauges assembly have been done at one workstation (v) Automated machinery	
15	Final inspection	(i) Lack in planning (ii) Repeatedly deploy new workers for inspection (iii) Unawareness of the work	Smart manufacturing, artificial intelligence, embedded system	(i) Improvement in planning (ii) Experienced staff have deployed for inspection (iii) Organized meeting and training (iv) Automated machinery and embedded system (v) Digitalization	13.15

established the connection between the cloud manufacturing platform and field-level manufacturing equipment. Peng et al. [103] proposed a conceptual framework for flexible manufacturing strategy using the industrial internet. The study reviewed industrial Internet-enabled implementations in China in response to COVID-19 and discussed it from 3Rs' perspective, that is, supply chain resilience, manufacturer capacity recovery, and emergency response. The result provided preliminary study reflections and a flexible manufacturing strategy in the wake of the COVID-19 pandemic. Meissner et al. [104] identified different starting points for digital shop floor management using a cluster analysis based on survey data. The study showed three initial conditions for implementing digital shop floor

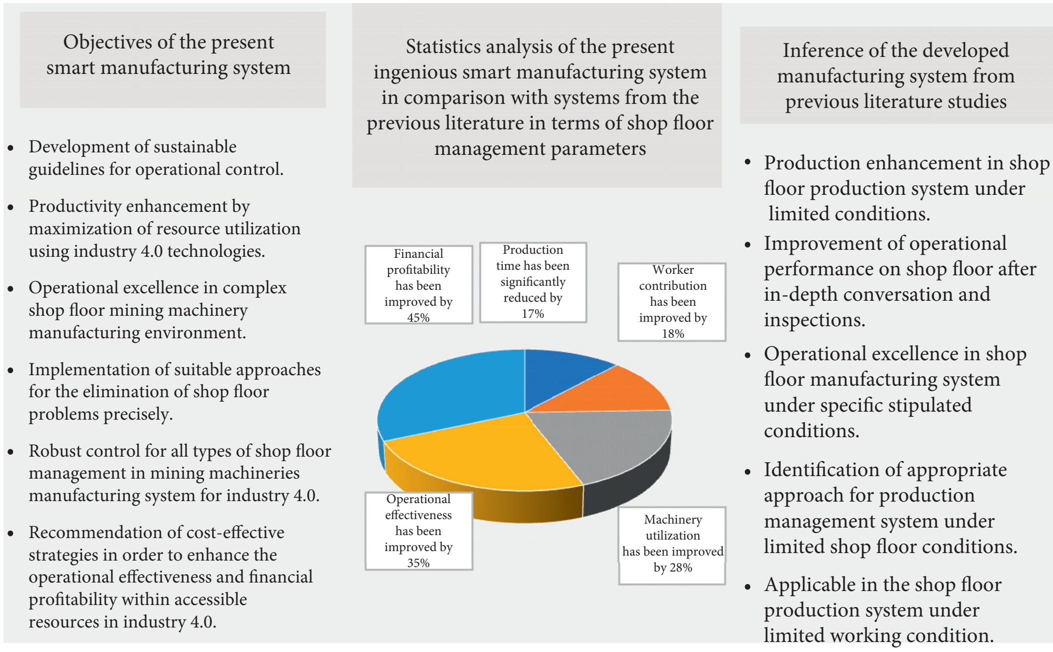


Figure 12: Comparatively benchmark analysis of the present smart manufacturing system for industry 4.0.

management in the German metal and electrical industry that can describe gradually. Furthermore, the results showed that digital shop floor management could remain competitive over the long term across all companies.

6.4. Sustainable Shop Floor Management System and Industry 4.0 Technologies. Implementing an efficient process optimization approach with industry 4.0 technologies for operational control in a complex environment plays a vital role in shop floor management [2, 3, 11, 17, 25, 32, 39, 55, 69, 82]. Industry 4.0 technologies enormously enhance productivity by maximizing operational excellence, workers' contributions, overall equipment effectiveness, and process adaptability [1, 3, 20, 26, 30, 88, 90, 92, 105]. The management team members emphasize using the process optimization approaches with industry 4.0 technologies because of problems faced in production control in complex shop floor manufacturing environments [4, 6, 27, 91]. Industry 4.0 technologies mainly include the internet of things, artificial intelligence, artificial neural network, digitalization, and asset tracking system. These technologies help enhance the overall efficacy of the process optimization approach on the shop floor and enhance productivity within limited resources. It has been observed that the production team members feel mental and physical comforted by implementing the process optimization approaches with industry 4.0 technologies in the complex production environment. Therefore, the efficiency of the shop floor management system can be improved by the integration of the process optimization approach with industry 4.0 technologies. Furthermore, the integrated approach can enhance industrial sustainability in complex production systems by establishing a safe and waste-free environment on the shop floor.

6.5. Performance of Lean Approach and Industry 4.0 Technologies. A methodology has been developed in the present research work to enhance industrial sustainability in industry 4.0 by eliminating waste using lean and smart manufacturing. The developed methodology is able to provide a positive working condition by establishing the aesthetic environment in shop floor departments by eliminating waste. The lean approach aims to maximize productivity by avoiding non-value-added activities in production planning on the shop floor. Non-value added activities are types that never provide any value in product/production processes, so the shop floor management teams always focus on making a strategy for the elimination of waste by avoiding non-value-added activities in production planning. Industry 4.0 technologies boost the effectiveness of the lean approach in operational control on the production shop floor. Industry 4.0 uses various techniques to enhance the lean approach including an asset tracking system, automated guided vehicle, digitization, radiofrequency identification system, smart condition monitoring system, and big data analytics. In the present scenario, the management team prefers industry 4.0 techniques to enhance productivity by maintaining industrial sustainability within limited constraints. It has been observed that satisfactory results may not be obtained by applying the methodologies developed in the previous research works to other management systems [3, 8, 22, 24, 27, 50, 64, 67, 69, 84]. Therefore, in the present research work, such a management system has been developed that can be applied in all types of production conditions. The developed methodology has been verified and proved by implementing it in different actual production conditions. The results show that the developed methodology provided a robust management system by effectively improving production time, worker's contribution, machinery utilization, operational excellence, and financial profitability by 17%, 18%, 28%, 35%, and 45%, respectively. Therefore, the developed methodology would be preferable by management team members because it helps in the decision-making phase according to problems and wastes found in different industrial scenarios and could be proved to benchmark for control and enhance operational excellence in industry 4.0. Figure 12 describes the benefits of the developed smart management system in comparison to previous systems in terms of production shop floor management factors.

6.6. Relation between Industry 4.0 and Lean Approach. The lean approach can enhance work performance by necessary improvements in the shop floor management system, and industry 4.0 techniques provide a method to improve productivity by maximizing the utilization of resources. The developed innovative system in the present research uses the integration of lean and industry 4.0 techniques to enhance work performance by optimizing the utilization of resources. The developed system provides industrial sustainability by improving various shop floor factors, including production time, work area, worker contribution, available time, and machinery performance. The developed system has been validated by implementing in an actual production condition of industry 4.0. The results obtained by the production system showed that the developed system is able to enhance productivity within limited constraints. Furthermore, the developed system proved cost-effective by minimizing unnecessary uses of resources. The lean approach improves work performance by eliminating unnecessary activities in the production processes, while industry 4.0 techniques improve operational conditions by establishing advanced systems on the production shop floor. In the present scenario, the shop floor management teams emphasize establishing industrial sustainability by improving operational excellence with minimum consumption of resources. Therefore, the developed system would be preferred by industry individuals in the shop floor management system because the developed system was found able to enhance industrial sustainability and financial profitability within limited constraints.

6.7. Potential Contribution of the Proposed Smart Manufacturing System in Managerially Impacts for Earthmoving/Mining Machinery Manufacturing Shop Floor Management. The proposed smart production management system has been developed on a lean and smart manufacturing approach to control production processes using limited resources and enhance productivity in existing financial conditions. The developed system provides a sustainable strategy for identifying problems and eliminating waste by monitoring operational performance on the shop floor. The integration of lean and innovative approaches is considered efficient by the shop floor management teams because this integration can enhance productivity and financial profitability within limited constraints [2, 3, 6, 20, 22, 26, 39, 55, 67, 74, 90, 105]. Furthermore, the developed smart shop floor management system helps in the decision-making stage to implement a suitable approach for maximizing productivity with available resources. Thus, it has been concluded that the lean and smart approach makes the shop floor management system effective and superior for production management by eliminating waste in the industry 4.0 environment.

7. Conclusions and Future Outlook

In the present research article, a smart production management system has been proposed to identify problems and challenges faced on the production shop floor in industry 4.0. The main findings obtained by the present research work are as follows:

(i) It has been observed that the innovative system developed can efficiently identify problems and challenges at the start of production processes in complex production shop floor conditions, thereby avoiding financial losses from production in industry 4.0

(ii) The developed system provides an agile system and guidelines for enhancement in industrial sustainability in heavy machinery manufacturing units.

(iii) It has been found that the developed system provided improvement in production time, worker's contribution, machinery utilization, operational excellence, and financial profitability by 17%, 18%, 28%, 35%, and 45%, respectively. In addition, it has been proved that using automated equipment in production lines and reduced working hours provide mental and physical comfort to workers. As a result, unprecedented improvement can be achieved in the production shop floor management.

(iv) A comprehensive analysis of previous research work found that smart manufacturing, lean smart manufacturing, artificial intelligence, machine learning, and the internet of things are emerging techniques for shop floor management in industry 4.0. They can be applied to maintain industrial stability in all types of production situations.

(v) The authors of the present research article strongly believe that the developed system would provide an intelligent key to industry individuals for enhancement in industrial sustainability of industry 4.0.

For the future prospects, and to concentrate on the present scenario of industry 4.0, the production shop floor management team members emphasize developing an innovative system to enhance industrial sustainability within available resources. A smart shop floor management system has been developed in the present research work to accomplish this need of the production management teams. The efficacy of the developed model has been tested in an actual complex shop floor condition of an earthmoving machinery manufacturing unit. The result showed that the developed system efficiently controlled the shop floor management in heavy machinery manufacturing systems, including industry 4.0, by implementing a suitable approach to eliminate production problems and waste elimination. In future research, the adaptability of the developed system may be improved by applying it in other shop floor environments of industry 4.0. Furthermore, the proposed shop floor management system can be improved by integrating with different lean and intelligent approaches.

Abbreviations

LM: Lean manufacturing
LSS: Lean Six Sigma
VSM: Value stream mapping
SMED: Single minute exchange of die
TPM: Total productive maintenance
JIT: Just in time
TQM: Total quality management
SOP: Standard operating procedure
SLP: Systematic layout planning
LT: Lead time
PT: Production time
CO: Changeover time
NR: Number of operators
CT: Cycle time
AT: Available time
TT: Takt time
IT: Idle time
UT: Uptime
TCT: Total cycle time
TIT: Total idle time
WT: Working time
BT: Break time
PD: Production per day
NVAA: Non-value-added activities.

Data Availability

The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] M. Ramadan, B. Salah, M. Othman, and A. A. Ayubali, "Industry 4.0-based real-time scheduling and dispatching in lean manufacturing systems," *Sustainability*, vol. 12, no. 6, Article ID 2272, 2020.

[2] V. Tripathi, S. Saraswat, and G. D. Gautam, "A study on implementation of various approaches for shop floor management," *Lecture Notes in Electrical Engineering*, vol. 766, pp. 371–387, 2021.

[3] V. Tripathi, S. Chattopadhyaya, A. K. Mukhopadhyay et al., "An innovative agile model of smart lean-green approach for sustainability enhancement in industry 4.0," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 7, no. 4, p. 215, 2021.

[4] S.-V. Buer, J. O. Strandhagen, and F. T. S. Chan, "The link between industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda," *International Journal of Production Research*, vol. 56, no. 8, pp. 2924–2940, 2018.

[5] V. Tripathi, S. Chattopadhyaya, A. Bhadauria et al., "An agile system to enhance productivity through a modified value stream mapping approach in industry 4.0: a novel approach," *Sustainability*, vol. 13, no. 21, Article ID 11997, 2021.

[6] P. Zheng, H. wang, Z. Sang et al., "Smart manufacturing systems for Industry 4.0: conceptual framework, scenarios, and future perspectives," *Frontiers of Mechanical Engineering*, vol. 13, no. 2, pp. 137–150, 2018.

[7] R. Ben Ruben, S. Vinodh, and P. Asokan, "Implementation of Lean Six Sigma framework with environmental considerations in an Indian automotive component manufacturing firm: a case study," *Production Planning & Control*, vol. 28, no. 15, pp. 1193–1211, 2017.

[8] M. Sony, "Industry 4.0 and lean management: a proposed integration model and research propositions," *Production & Manufacturing Research*, vol. 6, no. 1, pp. 416–432, 2018.

[9] G. L. Tortorella, R. Giglio, and D. H. van Dun, "Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement," *International Journal of Operations & Production Management*, vol. 39, no. 6/7/8, pp. 860–886, 2019.

[10] S. S. Kamble, A. Gunasekaran, A. Ghadge, and R. Raut, "A performance measurement system for industry 4.0 enabled smart manufacturing system in SMMEs- A review and empirical investigation," *International Journal of Production Economics*, vol. 229, Article ID 107853, 2020.

[11] M. S. Amjad, M. Z. Rafique, and M. A. Khan, "Leveraging optimized and cleaner production through industry 4.0," *Sustainable Production and Consumption*, vol. 26, pp. 859–871, 2021.

[12] G. L. Tortorella and D. Fettermann, "Implementation of industry 4.0 and lean production in brazilian manufacturing companies," *International Journal of Production Research*, vol. 56, no. 8, pp. 2975–2987, 2018.

[13] N. Dahmani, K. Benhida, A. Belhadi, S. Kamble, S. Elfezazi, and S. K. Jauhar, "Smart circular product design strategies towards eco-effective production systems: a lean eco-design industry 4.0 framework," *Journal of Cleaner Production*, vol. 320, Article ID 128847, 2021.

[14] L. Varela, A. Araújo, P. Ávila, H. Castro, and G. Putnik, "Evaluation of the relation between lean manufacturing, industry 4.0, and sustainability," *Sustainability*, vol. 11, no. 5, pp. 1439–1519, 2019.

[15] A. Chiarini and M. Kumar, "Lean six sigma and industry 4.0 integration for operational excellence: evidence from Italian manufacturing companies," *Production Planning & Control*, vol. 32, no. 13, pp. 1084–1101, 2021.

[16] R. Saxby, M. Cano-Kourouklis, and E. Viza, "An initial assessment of Lean Management methods for Industry 4.0," *The TQM Journal*, vol. 32, no. 4, pp. 587–601, 2020.

[17] M. P. Ciano, P. Dallasega, G. Orzes, and T. Rossi, "One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study," *International Journal of Production Research*, vol. 59, no. 5, pp. 1386–1410, 2021.

[18] A. Ghaithan, M. Khan, A. Mohammed, and L. Hadidi, "Impact of industry 4.0 and lean manufacturing on the sustainability performance of plastic and petrochemical

organizations in Saudi Arabia," *Sustainability*, vol. 13, no. 20, 20 pages, Article ID 11252, 2021.

[19] M. Rossini, F. Costa, G. L. Tortorella, and A. Portioli-Staudacher, "The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers," *International Journal of Advanced Manufacturing Technology*, vol. 102, no. 9-12, pp. 3963–3976, 2019.

[20] Z. M. Çınar, A. Abdussalam Nuhu, Q. Zeeshan, O. Korhan, M. Asmael, and B. Safaei, "Machine learning in predictive maintenance towards sustainable smart manufacturing in industry 4.0," *Sustainability*, vol. 12, no. 19, Article ID 8211, 2020.

[21] A. Aziz, O. Schelén, and U. Bodin, "A study on industrial IoT for the mining industry: synthesized architecture and open research directions," *IoT*, vol. 1, no. 2, pp. 529–550, 2020.

[22] T.-L. Nguyen, "STEAM-ME: a novel model for successful kaizen implementation and sustainable performance of SMEs in vietnam," *Complexity*, vol. 2019, Article ID 6048195, 23 pages, 2019.

[23] W. D. Leong, S. Y. Teng, B. S. How et al., "Enhancing the adaptability: lean and green strategy towards the industry revolution 4.0," *Journal of Cleaner Production*, vol. 273, Article ID 122870, 2020.

[24] V. Tripathi, S. Saraswat, and G. D. Gautam, "Development of a systematic framework to optimize the production process in shop floor management," *Lecture Notes in Mechanical Engineering*, vol. 2021, pp. 57–66, 2021.

[25] S. Choudhary, R. Nayak, M. Dora, N. Mishra, and A. Ghadge, "An integrated lean and green approach for improving sustainability performance: a case study of a packaging manufacturing SME in the U.K," *Production Planning & Control*, vol. 30, no. 5-6, pp. 353–368, 2019.

[26] A. Cherrafi, S. Elfezazi, K. Govindan, J. A. Garza-Reyes, K. Benhida, and A. Mokhlis, "A framework for the integration of Green and Lean Six Sigma for superior sustainability performance," *International Journal of Production Research*, vol. 55, no. 15, pp. 4481–4515, 2017.

[27] S. Kamble, A. Gunasekaran, and N. C. Dhone, "Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies," *International Journal of Production Research*, vol. 58, no. 5, pp. 1319–1337, 2020.

[28] A. Belhadi, S. S. Kamble, K. Zkik, A. Cherrafi, and F. E. Touriki, "The integrated effect of big data analytics, lean six sigma and green manufacturing on the environmental performance of manufacturing companies: the case of north africa," *Journal of Cleaner Production*, vol. 252, Article ID 119903, 2020.

[29] M. Tayyab, B. Sarkar, and B. Yahya, "Imperfect multi-stage lean manufacturing system with rework under fuzzy demand," *Mathematics*, vol. 7, no. 1, p. 13, 2018.

[30] R. Črešnar, V. Potočan, and Z. Nedelko, "Speeding up the implementation of industry 4.0 with management tools: empirical investigations in manufacturing organizations," *Sensors*, vol. 20, no. 12, Article ID 3469, 2020.

[31] V. Tripathi and S. Saraswat, "Lean manufacturing for shop floor of automotive industries: a study," *Journal of Experimental & Applied Mechanics*, vol. 9, no. 2, pp. 258–265, 2018.

[32] G. Yadav, S. Luthra, D. Huisingh, S. K. Mangla, B. E. Narkhede, and Y. Liu, "Development of a lean manufacturing framework to enhance its adoption within manufacturing companies in developing economies," *Journal of Cleaner Production*, vol. 245, Article ID 118726, 2020.

[33] J. Östlin and H. Ekholm, "Lean production principles in remanufacturing - a case study at a toner cartridge remanufacturer," in *Proceedings of the IEEE International Symposium on Electronics and the Environment 2007*, pp. 216–221, Orlando, FL, USA, May 2007.

[34] D. Seth and V. Gupta, "Application of value stream mapping for lean operations and cycle time reduction: an Indian case study," *Production Planning & Control*, vol. 16, no. 1, pp. 44–59, 2005.

[35] A. M. Gati-Wechsler and A. S. Torres, "The influence of lean concepts on the product innovation process of a brazilian shoe manufacturer," in *Proceedings of the PICMET Portl. Int. Cent. Manag. Eng. Technol. Proc. 2008*, pp. 1137–1144, Cape Town, South Africa, August 2008.

[36] A. K. Sahoo, N. K. Singh, R. Shankar, and M. K. Tiwari, "Lean philosophy: implementation in a forging company," *International Journal of Advanced Manufacturing Technology*, vol. 36, no. 5–6, pp. 451–462, 2008.

[37] L. N. Pattanaik and B. P. Sharma, "Implementing lean manufacturing with cellular layout: a case study," *International Journal of Advanced Manufacturing Technology*, vol. 42, no. 7–8, pp. 772–779, 2009.

[38] B. Singh and S. K. Sharma, "Value stream mapping as a versatile tool for lean implementation: an Indian case study of a manufacturing firm," *Measuring Business Excellence*, vol. 13, no. 3, pp. 58–68, 2009.

[39] S. Vinodh, K. R. Arvind, and M. Somanaathan, "Application of value stream mapping in an Indian camshaft manufacturing organisation," *Journal of Manufacturing Technology Management*, vol. 21, no. 7, pp. 888–900, 2010.

[40] A. R. Rahani and M. Al-Ashraf, "Production flow analysis through value stream mapping: a lean manufacturing process case study," *Procedia Engineering*, vol. 41, no. Iris, pp. 1727–1734, 2012.

[41] N. A. A. Rahman, S. M. Sharif, and M. M. Esa, "Lean manufacturing case study with kanban system implementation," *Procedia Economics and Finance*, vol. 7, no. Icebr, pp. 174–180, 2013.

[42] J. C. Chen, C. H. Cheng, P. B. Huang, K. J. Wang, C. J. Huang, and T. C. Ting, "Warehouse management with lean and RFID application: a case study," *International Journal of Advanced Manufacturing Technology*, vol. 69, no. 1–4, pp. 531–542, 2013.

[43] R. G. Bertolini, "Lean manufacturing in the valve pre-assembly area of a bottling lines production plant: an Italian case study," in *Proceedings of the 2013 International Conference on Industrial Engineering and Systems Management (IESM)*, Agdal, Morocco, October, 2013.

[44] Z. Longhan, L. Hong, and X. Shiwei, "Production process improvement based on value stream mapping for CY company," in *Proceedings of the 2013 6th International Conference on Information Management, Innovation Management and Industrial Engineering*, vol. 3, pp. 226–229, Xi'an, China, November 2013.

[45] K. L. Jeyaraj, C. Muralidharan, R. Mahalingam, and S. G. Deshmukh, "Applying value stream mapping technique for production improvement in a manufacturing company: a case study," *Journal of the Institution of Engineers: Series C*, vol. 94, no. 1, pp. 43–52, 2013.

[46] B. Das, U. Venkatadri, and P. Pandey, "Applying lean manufacturing system to improving productivity of airconditioning coil manufacturing," *International Journal of Advanced Manufacturing Technology*, vol. 71, no. 1–4, pp. 307–323, 2014.

[47] G. F. Barbosa, J. Carvalho, and E. V. G. Filho, "A proper framework for design of aircraft production system based on lean manufacturing principles focusing to automated processes," *International Journal of Advanced Manufacturing Technology*, vol. 72, no. 9–12, pp. 1257–1273, 2014.

[48] M. K. Kumar, A. J. Rajan, R. K. B. Navas, and S. S. Rubinson, "Application of lean manufacturing in mass production system A case study in Indian manufacturing unit," in *Proceedings of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 702–706, Selangor, Malaysia, December 2014.

[49] A. Ismail, J. A. Ghani, M. N. Ab Rahman, B. Md Deros, and C. H. Che Haron, "Application of lean six sigma tools for cycle time reduction in manufacturing: case study in biopharmaceutical industry," *Arabian Journal for Science and Engineering*, vol. 39, no. 2, pp. 1449–1463, 2014.

[50] S. Singh Amin, R. Atre, A. Vardia, and B. Sebastian, "Lean machine manufacturing at Munjal Showa limited," *International Journal of Productivity and Performance Management*, vol. 63, no. 5, pp. 644–664, 2014.

[51] Z. G. d. Santos, L. Vieira, and G. Balbinotti, "Lean manufacturing and ergonomic working conditions in the automotive industry," *Procedia Manufacturing*, vol. 3, pp. 5947–5954, 2015.

[52] B. G. Mwanza and C. Mbohwa, "Design of a total productive maintenance model for effective implementation: case study of a chemical manufacturing company," *Procedia Manufacturing*, vol. 4, pp. 461–470, 2015.

[53] S. Choi, B. H. Kim, and S. Do Noh, "A diagnosis and evaluation method for strategic planning and systematic design of a virtual factory in smart manufacturing systems," *International Journal of Precision Engineering and Manufacturing*, vol. 16, no. 6, pp. 1107–1115, 2015.

[54] J. M. Rohani and S. M. Zahraee, "Production line analysis via value stream mapping: a lean manufacturing process of color industry," *Procedia Manufacturing*, vol. 2, pp. 6–10, 2015.

[55] M. M. Esa, N. A. A. Rahman, and M. Jamaludin, "Reducing high setup time in assembly line: a case study of automotive manufacturing company in Malaysia," *Procedia - Social and Behavioral Sciences*, vol. 211, pp. 215–220, 2015.

[56] J.-C. Lu and T. Yang, "Implementing lean standard work to solve a low work-in-process buffer problem in a highly automated manufacturing environment," *International Journal of Production Research*, vol. 53, no. 8, pp. 2285–2305, 2015.

[57] S. Tyagi, A. Choudhary, X. Cai, and K. Yang, "Value stream mapping to reduce the lead-time of a product development process," *International Journal of Production Economics*, vol. 160, pp. 202–212, 2015.

[58] J. Choomlucksana, M. Ongsaranakorn, and P. Suksabai, "Improving the productivity of sheet metal stamping subassembly area using the application of lean manufacturing principles," *Procedia Manufacturing*, vol. 2, pp. 102–107, 2015.

[59] S. A. Ali Naqvi, M. Fahad, M. Atir, M. Zubair, and M. M. Shehzad, "Productivity improvement of a manufacturing facility using systematic layout planning," *Cogent Eng*, vol. 3, no. 1, 2016.

[60] P. F. Andrade, V. G. Pereira, and E. G. Del Conte, "Value stream mapping and lean simulation: a case study in automotive company," *International Journal of Advanced Manufacturing Technology*, vol. 85, no. 1-4, pp. 547–555, 2016.

[61] A. J. Thomas, M. Francis, R. Fisher, and P. Byard, "Implementing Lean Six Sigma to overcome the production challenges in an aerospace company," *Production Planning & Control*, vol. 27, no. 7–8, pp. 1–13, 2016.

[62] P. Garre, V. V. S. Nikhil Bharadwaj, P. Shiva Shashank, M. Harish, and M. Sai Dheeraj, "Applying lean in aerospace manufacturing," *Materials Today Proceedings*, vol. 4, no. 8, pp. 8439–8446, 2017.

[63] A. Asif and R. Singh, "Further cost reduction of battery manufacturing," *Batteries*, vol. 3, no. 4, p. 17, 2017.

[64] A.-A. Dadashnejad and C. Valmohammadi, "Investigating the effect of value stream mapping on overall equipment effectiveness: a case study," *Total Quality Management and Business Excellence*, vol. 30, no. 3-4, pp. 466–482, 2019.

[65] I. C. Diaz, Y. Jin, and E. Ares, "Cycle time study of wing spar assembly on aircraft factory," *Procedia Manufacturing*, vol. 13, pp. 1019–1025, 2017.

[66] J. D. Morales Méndez and R. S. Rodriguez, "Total productive maintenance (TPM) as a tool for improving productivity: a case study of application in the bottleneck of an auto-parts machining line," *International Journal of Advanced Manufacturing Technology*, vol. 92, no. 1-4, pp. 1013–1026, 2017.

[67] K. Nagadi, L. Rabelo, M. Basingab, A. T. Sarmiento, A. Jones, and A. Rahal, "A hybrid simulation-based assessment framework of smart manufacturing systems," *International Journal of Computer Integrated Manufacturing*, vol. 31, no. 2, pp. 115–128, 2018.

[68] J. A. Garza-Reyes, V. Kumar, S. Chaikittisilp, and K. H. Tan, "The effect of lean methods and tools on the environmental performance of manufacturing organisations," *International Journal of Production Economics*, vol. 200, pp. 170–180, 2018.

[69] E. V. Gijo, R. Palod, and J. Antony, "Lean Six Sigma approach in an Indian auto ancillary conglomerate: a case study," *Production Planning & Control*, vol. 29, no. 9, pp. 761–772, 2018.

[70] S. Dorota and P. Litwin, "Value stream mapping and system dynamics integration for manufacturing line modelling and analysis," *International Journal of Production Economics*, vol. 208, pp. 400–411, 2019.

[71] V. G. Cannas, M. Pero, R. Pozzi, and T. Rossi, "Complexity reduction and kaizen events to balance manual assembly lines: an application in the field," *International Journal of Production Research*, vol. 56, no. 11, pp. 3914–3931, 2018.

[72] S. Kumar, A. K. Dhingra, and B. Singh, "Process improvement through Lean-Kaizen using value stream map: a case study in India," *International Journal of Advanced Manufacturing Technology*, vol. 96, no. 5-8, pp. 2687–2698, 2018.

[73] B. Suhardi, N. Anisa, and P. W. Laksono, "Minimizing waste using lean manufacturing and ECRS principle in Indonesian furniture industry," *Cogent Eng*, vol. 6, no. 1, pp. 1–13, 2019.

[74] M. Saqlain, M. Piao, Y. Shim, and J. Y. Lee, "Framework of an IoT-based industrial data management for smart manufacturing," *Journal of Sensor and Actuator Networks*, vol. 8, no. 2, pp. 25–2, 2019.

[75] P. M. Masuti and U. A. Dabade, "Lean manufacturing implementation using value stream mapping at excavator manufacturing company," *Materials Today Proceedings*, vol. 19, pp. 606–610, 2019.

[76] P. V. Ramani and L. K. Lingan, "Developing a lean model to reduce the design process cost of gas insulated switchgear foundation using value stream mapping - a case study,"

International Journal of Construction Management, vol. 0, no. 0, pp. 1–9, 2019.
[77] S. Krishna Priya, V. Jayakumar, and S. Suresh Kumar, "Defect analysis and lean six sigma implementation experience in an automotive assembly line," *Materials Today Proceedings*, vol. 22, pp. 948–958, 2020.
[78] W. Liao and T. Wang, "A novel collaborative optimization model for job shop production-delivery considering time window and carbon emission," *Sustainability*, vol. 11, no. 10, Article ID 2781, 2019.
[79] W. Shou, J. Wang, P. Wu, and X. Wang, "Value adding and non-value adding activities in turnaround maintenance process: classification, validation, and benefits," *Production Planning & Control*, vol. 31, no. 1, pp. 60–77, 2019.
[80] S. S. Sharma, D. D. Shukla, and B. P. Sharma, *Analysis of Lean Manufacturing Implementation in SMEs: A " 5S " Technique*, Springer, Singapore, 2019.
[81] M. Abubakr, A. T. Abbas, I. Tomaz, M. S. Soliman, M. Luqman, and H. Hegab, "Sustainable and smart manufacturing: an integrated approach," *Sustainability*, vol. 12, no. 6, pp. 2280–2319, 2020.
[82] D. Torres, C. Pimentel, and S. Duarte, "Shop floor management system in the context of smart manufacturing: a case study," *International Journal of Lean Six Sigma*, vol. 11, no. 5, pp. 823–848, 2020.
[83] M. Mohan Prasad, J. M. Dhiyaneswari, J. Ridzwanul Jamaan, S. Mythreyan, and S. M. Sutharsan, "A framework for lean manufacturing implementation in Indian textile industry," *Materials Today Proceedings*, vol. no, 2020.
[84] S. Mittal, M. A. Khan, J. K. Purohit, K. Menon, D. Romero, and T. Wuest, "A smart manufacturing adoption framework for SMEs," *International Journal of Production Research*, vol. 58, no. 5, pp. 1555–1573, 2020.
[85] R. Balamurugan, R. Kirubagharan, and C. Ramesh, "Implementation of lean tools and techniques in a connecting rod manufacturing industry," *Materials Today Proceedings*, vol. 33, 2020.
[86] C.-F. Chien and C.-C. Chen, "Data-driven framework for tool health monitoring and maintenance strategy for smart manufacturing," *IEEE Transactions on Semiconductor Manufacturing*, vol. 33, no. 4, pp. 644–652, 2020.
[87] A. Amrani and Y. Ducq, "Lean practices implementation in aerospace based on sector characteristics: methodology and case study," *Production Planning & Control*, vol. 0, no. 0, pp. 1–23, 2020.
[88] A. Frankó, G. Vida, and P. Varga, "Reliable identification schemes for asset and production tracking in industry 4.0," *Sensors*, vol. 20, no. 13, pp. 3709–3724, 2020.
[89] P. D. Gaspar, C. M. Fernandez, V. N. G. J. Soares, J. M. L. P. Caldeira, and H. Silva, "Development of technological capabilities through the internet of things (IoT): survey of opportunities and barriers for IoT implementation in Portugal's agro-industry," *Applied Sciences*, vol. 11, no. 8, p. 3454, 2021.
[90] J. Reyes, J. Mula, and M. Díaz-Madroñero, "Development of a conceptual model for lean supply chain planning in industry 4.0: multidimensional analysis for operations management," *Production Planning & Control*, vol. 0, no. 0, pp. 1–16, 2021.
[91] I. P. Vlachos, R. M. Pascazzi, G. Zobolas, P. Repoussis, and M. Giannakis, "Lean manufacturing systems in the area of Industry 4.0: a lean automation plan of AGVs/IoT integration," *Production Planning & Control*, vol. 2021, Article ID 1917720, 14 pages, 2021.
[92] F. Brocal, C. González, D. Komljenovic, P. F. Katina, M. A. Sebastián, and J. L. Garciá-Alcaraz, "Emerging risk management in industry 4.0: an approach to improve organizational and human performance in the complex systems," *Complexity*, vol. 2019, Article ID 2089763, 13 pages, 2019.
[93] V. Tripathi, S. Saraswat, G. Gautam, and D. Singh, "Shop floor productivity enhancement using a modified lean manufacturing approach," *Lecture Notes in Mechanical Engineering*, vol. 2021, pp. 219–227, 2021.
[94] V. Tripathi, S. Saraswat, and G. D. Gautam, "Improvement in shop floor management using ANN coupled with VSM: a case study," *Proceedings of the Institution of Mechanical Engineers - Part C: Journal of Mechanical Engineering Science*, vol. 2022, Article ID 095440622110620, March 2022.
[95] J. P. Womack and D. T. Jones, *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*, Simon & Schuster, New York, 1996.
[96] M. Müller, E. Alexandi, and J. Metternich, "Digital shop floor management enhanced by natural language processing," *Procedia CIRP*, vol. 96, pp. 21–26, 2021.
[97] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, "Industry 4.0 and Industry 5.0-Inception, conception and perception," *Journal of Manufacturing Systems*, vol. 61, pp. 530–535, 2021.
[98] D. Mourtzis, "Simulation in the design and operation of manufacturing systems: state of the art and new trends," *International Journal of Production Research*, vol. 58, no. 7, pp. 1927–1949, 2020.
[99] D. Mourtzis, J. Angelopoulos, and N. Panopoulos, "Robust engineering for the design of resilient manufacturing systems," *Applied Sciences*, vol. 11, no. 7, Article ID 3067, 2021.
[100] D. Mourtzis, J. Angelopoulos, and N. Panopoulos, "Design and development of an IoT enabled platform for remote monitoring and predictive maintenance of industrial equipment," *Procedia Manufacturing*, vol. 54, pp. 166–171, 2021.
[101] D. Mourtzis, "Machine tool 4.0 in the era of digital manufacturing," in *Proceedings of the 32nd European Modeling & Simulation Symposium (EMSS 2020)*, pp. 416–429, Athens, Greece, September 2020.
[102] C. Liu, Z. Su, X. Xu, and Y. Lu, "Service-oriented industrial internet of things gateway for cloud manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 73, Article ID 102217, 2022.
[103] T. Peng, Q. He, Z. Zhang, B. Wang, and X. Xu, "Industrial internet-enabled resilient manufacturing strategy in the wake of COVID-19 pandemic: a conceptual framework and implementations in China," *Chinese Journal of Mechanical Engineering*, vol. 34, no. 1, 2021.
[104] A. Meissner, D. Scherer, and J. Metternich, "Starting points for digital shop floor management in production enterprises," *Procedia CIRP*, vol. 104, pp. 212–216, 2021.
[105] V. Tripathi, S. Chattopadhyaya, A. K. Mukhopadhyay, S. Sharma, C. Li, and G. Di Bona, "A sustainable methodology using lean and smart manufacturing for the cleaner production of shop floor management in industry 4.0," *Mathematics*, vol. 10, no. 3, p. 347, 2022.

Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 9527219, 15 pages
https://doi.org/10.1155/2022/9527219

Research Article

Integrating the MCDM Method to Explore the Business Model Innovation in Taiwan: A Case Study in Affiliated Restaurants

Joyce Hsiu-Yu Chen,[1] Hsueh-Feng Chang ,[2] Hsiu-Chu Hung,[3] and Yu-Shan Lin[4]

[1]*Department of Food & Beverage Management, National Kaohsiung University of Hospitality and Tourism, Kaohsiung, Taiwan*
[2]*Department of Tourism Management, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan*
[3]*Department of Industrial Education and Technology, National Changhua University of Education, Changhua, Taiwan*
[4]*Department of Leisure Industry, National Chin-Yi University of Technology, Taichung, Taiwan*

Correspondence should be addressed to Hsueh-Feng Chang; anniechang@nkust.edu.tw

Received 29 October 2021; Revised 6 January 2022; Accepted 17 January 2022; Published 15 February 2022

Academic Editor: Kuei-Hu Chang

It is not easy for the hotel industry to develop a new business model. To find new consumers, Taiwan's hotel industry has learned from the successful experience of internal restaurants and set up affiliated restaurants. The innovative business model has become an important niche for grasping key technologies and expanding advantages in terms of food and beverage management outside the hotel building. Based on this, and on the application of resource theory, this research is based on the authors' previous research results which used resource-based theories as the basis to develop evaluation dimensions and criteria. This article continues this aspect and model, and merges MCDM models such as DEMATEL and DANP methods to formulate a research evaluation standard system for affiliated restaurants. According to the research results, there are four resource dimensions and eight measurement indicators for the development of key resources for affiliated restaurants; the importance of the four resources is in the following order: organizational ability, personal ability, tangible assets, and intangible assets, and the first two are the "causes" in the causal relationship. The important order of the eight measurement indicators is organizational resources, human resources, financial resources, physical resources, brand/business reputation resources, marketing resources, technical resources, and relationship resources; among them, human resources and financial resources are the most important factors which are the "causes" in the causal relationship. This study uses a multi-criteria decision-making model to explore the resource application, evaluation, and importance ranking of hotel development for affiliated restaurants, which provides a benchmark for the hotel industry to establish affiliated restaurants as an innovative business model. The study results can be referred to for the future and sustainable development of the hotel industry.

1. Introduction

Within a competitive environment, continuous innovation is an important factor for the sustainable operation of the business [1]. Innovation refers to a high-risk, innovative idea for owners, which is considered to have high-reward potential or extremely favorable commercial interest behaviors [2]. Therefore, enterprises must continuously innovate to maintain their competitive advantages, and innovation ability is the key factor for the success of enterprises [3]. Hospitality products are difficult to protect through patents and copyrights; therefore, continuous product innovation is needed for hospitality firms to stay ahead of competitors [4].

The hotel industry mainly offers rooms and dining areas. However, as the number of people choosing food-away-from-home in Taiwan is quite large now, dining rooms have become important sources of revenue for Taiwan's hotel industry. The food and beverage are good in quality but high in price. Furthermore, some dining rooms have been in operation for a long time, whose primary consumers are turning older year by year. Hoping to find new consumers and increase the revenue, the hotel industry replicates the successful experience of internal dining rooms of hotels to open affiliated restaurants and construct a new business model. Driven by department stores, cinemas, and other business districts, the inbound capacity and table turnover have improved, promoting the food and beverage industry's revenue to reach a new high [5]. Indeed, a good enterprise performance represents the abundance of revenue or resources, which means that performance is also a key to innovation [6]. A continuous innovation process helps restaurants heighten barriers to the establishment, keeping their portfolio ahead of the competition, which establishes a long-term competitive advantage [7]. Using market demands and grasping key technologies remains a key question for enterprises to expand their advantages [8].

The business model shows how different elements of a business fit together [9]. Business innovation is a complex and multifaceted phenomenon [10]. The business model needs to consider the rationality of cost and the acquisition of value benefits [11], and the innovation of business model has changed the industry outlook and redistributed industrial values [12–15]. The research of Chang, Chen, Wu, and Ke shows that, in the application of business model, there are nine main factors that affect the development of hotel sub-brands, the most important of which are channels, target customers, customer relationships, and key activities [16]. In recent years, Taiwanese hotels have set up sub-brands to open restaurants in limited locations like department stores, shopping centers, and others, driving a new trend in Taiwan's food and beverage industry. However, there are many requirements to meet before developing affiliated restaurants in tourist hotels, and affiliated restaurants have become a new issue in recent years. Past research cannot effectively explain how the hotel industry can use core resources and capabilities to achieve sustainable development with limited resources, which requires further in-depth discussion.

With the outbreak of the new crown epidemic (COVID-19) in 2020, the global epidemic has had a huge impact on the operation of the hospitality industry. Under the pressure of fierce competition, coupled with changes in consumer behavior affected by the epidemic, the competitive environment in the hotel industry has become increasingly severe. In order to create a competitive advantage, it is bound to provide services that are different from traditional ones, which is a challenge. In such a predicament, the competition among peers has intensified. The establishment of off-site restaurants in the hotel industry can be regarded as a new form of corporate organization. Therefore, it is necessary to deeply explore the causal relationship between the development of core resources and the impact indicators of affiliated restaurants, to form a tight business model, and to enhance or strengthen the overall synergy effect.

This study proposes a multi-criteria decision-making (MCDM) model to solve the problem of the key resources evaluation for the development of affiliated restaurants. Compared with statistical methods, MCDM only necessitates expert interview data from small-sized samples; it does not require the establishment of basic assumptions for criteria or variables. It manages to integrate survey data with expert assessment and provides decision-makers with valid management information that facilitates their formulating of optimal strategies [17]. Therefore, in order to continue the research on affiliated restaurants, this study further analyzes the relationship between the four resources and eight indicators established by Chen, et al. [18] to complete the construction of an innovative business model. The main purposes of this study are as follows: Firstly, the present study applied DEMATEL to calculate the correlation between the evaluation criteria, so as to establish the multi-criteria decision analysis framework for affiliated restaurants. Secondly, this study introduced DANP to calculate the weight of criteria that influence each other and laid down a set of criteria used to evaluate affiliated restaurants.

2. Literature Review

2.1. Affiliated Restaurants and Innovation. With the change of times, people's lifestyle, and diversified eating habits, and the increase of people choosing food-away-from-home, the food and beverage industry is booming now. The food and beverage industry creates new brands in exhibition stores with growing revenue [5]. Opening affiliated restaurants in Taiwan's hotel industry is a new topic now. Old and well-established internal restaurants of hotels have joined the trend of setting up affiliated restaurants to attract young people, encouraging the food and beverage industry to adopt a new outlook and business model. Regent Taipei Hotel was the first to set up an affiliated restaurant. Followed by The Landis Taipei Hotel, Shangri-La's Far Eastern Plaza Hotel Taipei, Le Meridien Taipei, LDC Hotels and Resorts Group, Grand Han-Lai Hotel, Ambassador Hotel Taipei, Gloria Hotel Group, and other five-star hotels copied the successful cooking experience of internal restaurants to establish sub-brands in department stores and other locations using an innovative business model. Chang et al. define a sub-brand as: launching a new product in an existing market with a new brand. That is to say, on the premise of not violating the core concept and spirit of the main brand, a new brand and logo will be created for different consumer groups or different brand positioning [16].

Enterprises can use innovation to grasp the market [1]. Also, the innovation can either be a new product, a new method, a kind of potential to create a new business market, or a behavior pattern to change competitors or consumers [19]. To avoid the unmatching of products and services with market demands, enterprises need to develop new products and services [20]. According to Tidd, Bessant and Pavitt, innovation is redesigning or improving the products, services, and methods for an organization to survive or grow and create more different competitive advantages [21]. Process innovations increase profits for the organization through improved efficiencies and reducing costs [22]. Enterprises pursuing innovation can adapt to the changing environment by creating new products or services to satisfy market demands [23]. As a rising star springing up in the food and beverage industry, the affiliated restaurant provides an opportunity for consumers and enterprises to create unique competitive advantages based on innovation. At the same time, being able to influence the food and beverage industry, innovation is a topic worthy of attention.

Therefore, Chen et al. adopted the resource-based theory to explore the core resources and impact indicators of the affiliated restaurant development for tourist hotels in Taiwan by using in-depth interviews and the Fuzzy Delphi Method. According to the results, there were four dimensions: "tangible assets," "intangible assets," "personal ability," and "organizational ability," and eight measurement indicators: "physical resources," "financial resources," "brand/business reputation resources," "technical resources," "relationship resources," "marketing resources," "human resources," and "organizational resources" [18]. That article has great findings on the study of the affiliated restaurant research, but unfortunately it does not analyze the relationship between all core resources and indicators. Understanding the core resource dimensions and indictors is not enough. The analysis of the importance and causal relationship between indicators should be added to grasp the key to the competitive advantage of the business model.

2.2. Business Model Innovation (BMI). The business model is described as a process of changing the innovation into valuable products or services, during which the rationality of cost and the acquisition of value benefits must be considered [11]. As the business model aims to create more value for consumers, it is important to regard the business model as a system to emphasize profit and value [9]. From the perspective of strategy, Hill and Jones defined a business model as a collection of excellent profit-generating strategies for companies to pursue competitive advantages [24]. Maintaining and establishing competitive advantages for hotels within a fast-changing environment to meet market demands and pursue sustainable growth requires more attention from enterprises.

Ludeke-Freund et al. proposed that business model innovation is a means to alter and extend firms' ability to act effectively and efficiently as with any type of innovation [25]. Enterprises should actively develop value activities to make a profit outweigh the cost through business models [11]. In recent years, the innovative business model created by Taiwan's old and established hotels in food and beverage management is vital to the hotel industry. In addition, how to use market demands and master key technologies is also very important for enterprises to expand their advantages [8]. Geissdoerfer et al. advocated that the process of business model construction and modification is the business model innovation and forms a part of business strategy [26]. However, it is not easy for the hotel industry to develop a new business model, growing instability of the environment and constant transformation processes which dictate the new rules for the market participants require increased attention from scientists [27]. In this study, a new set of business model integrating Multiple Criteria Decision-Making is proposed to find out the relationship between all the considerations, calculate the weight of each factor, and analyze the key selection criteria. Also, the plans are ranked in order of their merits according to the weights of various factors. The aim of this study is to improve the reliability and accuracy of the selection, which considers all factors to identify the best solution to an innovative business model for hotels to develop affiliated restaurants.

3. Methodology

Through a multi-criteria decision-making model, applying the results of Chen et al.'s research, the Decision-Making and Trial Evaluation Laboratory (DEMATEL) and the DEMATEL-based Analytic Network Process (DANP) method is mainly used for this study. The relevant research tools and steps are described as follows.

3.1. Research Framework. Based on the results of Chen et al. discussing the core resources for the development of affiliated restaurants [18], this study further merges MCDM models such as DEMATEL and DANP methods to formulate a research evaluation standard system for affiliated restaurants. The results of the previous study have concluded four resource dimensions, namely, tangible assets, intangible assets, personal ability, and organizational ability, and eight indicators, including physical resources, financial resources, brand/business reputation resources, technical resources, relationship resources, marketing resources, human resources, and organizational resources, as well as 31 evaluation factors. In the light of the four resource dimensions and eight indicators, this study presents a multi-criteria decision-making model of the DEMATEL-based ANP method (DANP). In this study, 2 professors who specialized in the related fields and 14 managers working in the affiliated restaurants with more than 6 years of experience in hospitality industry were invited to fill out the questionnaires; the effective recovery rate was 100%. The distribution status for their working tenure and experience is: 12.5% for less than 10 years, 50% for 11–15 years, 12.5% for 16–20 years, 19% for 21–25 years, and 6% for more than 26 years. Among these experts, there are 2 junior supervisors, 5 intermediate supervisors, 7 senior supervisors, and 2 scholars with catering backgrounds.

As mentioned above, this study adopts the multi-criteria decision-making model of DANP to understand the causality and relevance and analyze the weights and ranking of importance, thus providing a reference for relevant industries aimed at achieving sustainable operation to use resources when developing affiliated restaurants in a real sense.

3.2. Key Resources and Impact Indicators for the Development of Affiliated Restaurants. This study refers to the resources and indicators for developing affiliated restaurants summarized by Chen et al., divided into four resource dimensions, eight indicators, and 31 evaluation factors [18], as shown in Table 1. Based on four dimensions and eight indicators, this study presents a multi-criteria decision-making model of the DANP method.

Table 1: List of core resources, indicators, and evaluation factors of developing affiliated restaurants.

Goal	Dimensions	Indicators	Evaluation factors
Resources and indicators for the development of affiliated restaurants	Tangible assets	Physical resources	Area-effectiveness Perfect equipment sets Location/store base Planar configuration and thematic feature/design
		Financial resources	Sound financial structure Abundant investment funds Payback time-estimated investment costs and returns
	Intangible assets	Brand/business reputation resources	Registered trademark Customers' brand loyalty Client contract/cooperation contract-cooperative store Company's entire image/brand popularity
		Technical resources	License and technological exchange Product innovation and research and development ability Database—the establishment of consumers' database Patents—delicacies, equipment, and service workflow
		Relationship resources	Horizontal alliances Client internalization—to internalize customers Stable supply chains
		Marketing resources	Marketing and planning Brand development plan Information technology and multimedia Ability of familiarizing and discovering potential markets
	Personal ability	Human resources	Personnel allocation and training Special skills—license of chef, language ability, supervision Management ability/leadership Social networks/communication ability
	Organizational ability	Organizational resources	Organizational culture Administration and procurement Organization and memory learning Cross-organization cooperation networks Degree of profession for the organizational operation

Source: [18].

3.3. Using Decision-Making Trial and Evaluation Laboratory (DEMATEL) to Discuss the Cause-and-Effect Relationships and Correlations of the Affiliated Restaurants' Core Resources and Impact Indicators. This paper discusses the cause-and-effect relationships and correlations of the affiliated restaurants' core resources and impact indicators, and analyzes the procedures as follows:

Step 1. Defining elements and evaluation scales

In this paper, taking the aforementioned 16 experts as the object, conduct a survey for the opinion on the cause-and-effect relationships and correlations of the affiliated restaurants' core resources and impact indicators. There are five levels, 0, 1, 2, 3, and 4, which individually represents "no impact (0)," "low impact (1)," "middle impact (2)," "high impact (3)," and "extremely high impact (4)."

Step 2. Establishing Matrix A for the average of experts' opinions

The number of evaluation items is set as n. The degree of mutual influence for each evaluation item judged by a large number of experts (assessors) in this field is collected and organized. Each expert's questionnaire represents the nonnegative result matrix, $n \times n$. All experts' opinions are added up and averaged out to establish matrix A for the average of experts' opinions, where A_{ij} denotes the degree of impact of Item i on Item j. The matrix diagonal means its degree of impact on each item. Because there is no impact, the value of diagonal part is set as 0, as follows:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix}. \quad (1)$$

Step 3. Building Matrix D for the normalization of the average of experts' opinions

After the column vectors and row vectors of Matrix A for the average of experts' opinions are added up, the maximum value is set as the normalization standard r. Next, all of the numbers of Matrix A for the average of experts' opinions separately multiply $s = 1/r$, denoted as $D = s \cdot A$, to obtain Matrix D for the normalization of the average of experts' opinions, whose matrix diagonal is 0. Also, the maximum value for the sum of columns and the sum of rows is 1. They can be represented in equations (2) and (3):

$$D = s \cdot A, \quad (2)$$

$$s = \max\left[\frac{1}{\max_{1\le i\le n}\sum_{j=1}^{n}\left|A_{ij}\right|}, \frac{1}{\max_{1\le j\le n}\sum_{i=1}^{n}\left|A_{ij}\right|}\right]. \quad (3)$$

Step 4. Establishing the total influence-relation matrix T

After normalizing the average of experts' opinions to obtain Matrix D, $\lim_{k\longrightarrow\infty} D^k = 0$ (0 means zero matrix) is received, so it is formulated as $T = D/I - D$, where I is the unit matrix, and then the total influence-relation matrix T can be obtained, as shown in equation (4).

$$\begin{aligned} T &= \lim_{k\longrightarrow\infty}\left(D + D^2 + D^3 + \cdots + D^k\right), \\ &= \frac{D}{I - D}, \\ &= D(I - D)^{-1}. \end{aligned} \quad (4)$$

Step 5. Setting the threshold value and mapping the cause-and-effect graph

The total average of the total influence-relation matrix T is set as the threshold value α. If the value of the total influence-relation matrix T is smaller than α, it will be replaced by 0; otherwise, it will be kept. The dimensions/indicators of the relatively low impact in the total influence-relation matrix T can be removed to obtain a simplified total influence-relation matrix, the total influence-relation matrix T order to map the correlations in the cause-and-effect graph. In addition, the sum of each row and the sum of each column in the total influence-relation matrix T are added up to form $d + r$ and $d - r$; $d + r$ is set as the horizontal axis and $d - r$ is set as the vertical axis to map the cause-and-effect graph. With the help of the cause-and-effect graph, decision-makers can refer to the correlations, causes, and effects in the dimensions/indicators to plan and make proper decisions. The sum of each row and the sum of each column in the total influence-relation matrix T can be formulated as follows:

$$\begin{aligned} d &= \left(d_i\right)_{n\times 1} \\ &= \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1}, \end{aligned} \quad (5)$$

$$\begin{aligned} r &= \left(r_j\right)_{n\times 1} \\ &= \left(r_j\right)'_{1\times n} \\ &= \left[\sum_{i=1}^{n} t_{ij}\right]'_{1\times n}. \end{aligned} \quad (6)$$

3.4. Using DEMATEL-Based Analytic Network Process (DANP) to Construct Affiliated Restaurants' Core Resources and Impact Indicators and to Conduct the Analysis of Weights as Well as the Importance of Priority. DANP (DEMATEL-based ANP) is a mixed MCDM model, combining Decision-Making Trial and Evaluation Laboratory (DEMATEL) with Analytic Network Process (ANP) [28]. Its procedures are analyzed and explained as follows:

Step 1. Establishing the unweighted supermatrix W

This step is a key to combining DEMATEL with ANP to form DANP. Therefore, this paper especially transforms this step into a detailed computing process.

(1) Establishing the total influence-relation matrix T_C for the DEMATEL indicators

Based on equations (1) to (4) formulated by the method of DEMATEL, the total influence-relation matrix T_C for the received indicators is set as T_C, whose formula is as follows: $T_C = \begin{bmatrix} t_{11} & \cdots & t_{1j} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{i1} & \cdots & t_{ij} & \cdots & t_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{n1} & \cdots & t_{nj} & \cdots & t_{nn} \end{bmatrix}$, where t_{ij} denotes the total influence value of Indicator i to Indicator j, n and represents the total number of indicators.

(2) Establishing the normalized standard f_i of the total influence-relation matrix T_C for indicators

The normalized standard of the total influence-relation matrix T_C is set as f_i. The normalized standard f_i must follow the dimensions to conduct the calculation. It is supposed that Indicator 1 to Indicator 2 belong to the first dimension and Indicators 3 to 6 belong to the second dimension. The normalized standard f_i of the first two column numbers of Matrix T_C is the sum of first two column vectors of the total influence-relation matrix T_C for indicators, n value (s) of f_i in total. The normalized standard f_i of the third to the sixth column numbers of Matrix T_C is the sum of the third to the sixth column vectors of the total influence-relation matrix T_C for indicators, n value (s) of f_i (s) in total. They are illustrated in equations (7) to (10):

$$T_C = \begin{bmatrix} t_{11} & \cdots & t_{1j} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{i1} & \cdots & t_{ij} & \cdots & t_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{n1} & \cdots & t_{nj} & \cdots & t_{nn} \end{bmatrix}, \tag{7}$$

$$T_C\left[t_{ij}\right] = T_{ij}^C \begin{bmatrix} t_{11}^C & \cdots & t_{1j}^C & \cdots & t_{1n}^C \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{i1}^C & \cdots & t_{ij}^C & \cdots & t_{in}^C \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{n1}^C & \cdots & t_{nj}^C & \cdots & t_{nn}^C \end{bmatrix}, \tag{8}$$

$$T_{ij}^C = \begin{bmatrix} t_{11}^C & \cdots & t_{1j}^C & \cdots & t_{1n}^C \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{i1}^C & \cdots & t_{ij}^C & \cdots & t_{in}^C \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{n1}^C & \cdots & t_{nj}^C & \cdots & t_{nn}^C \end{bmatrix}^{f_1=\sum_{j=1}^{n} t_{1j}^C}, \tag{9}$$

$$f_i = \sum_{j=1}^{n} t_{ij}^C, \tag{10}$$

(3) Establishing the total influence-relation matrix T_C^* for the normalized indicators

The total influence-relation matrix T_C^* for the normalized indicators should be calculated based on the dimensions, following the assumption of the previous step. The computing method of the total influence-relation matrix T_C^* for the normalized indicators is to divide the values of Matrix T_C one by one by the normalized standard f_i of its row so as to obtain the total influence-relation matrix T_C^* for the normalized indicators, as shown in equation (11). The normalized standard f_i is formulated as (9) and (10).

$$T_C^* = \begin{bmatrix} \frac{t_{11}}{f_1} & \cdots & \frac{t_{1j}}{f_1} & \cdots & \frac{t_{1n}}{f_1} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{t_{i1}}{f_i} & \cdots & \frac{t_{ij}}{f_i} & \cdots & \frac{t_{in}}{f_i} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{t_{n1}}{f_n} & \cdots & \frac{t_{nj}}{f_n} & \cdots & \frac{t_{nn}}{f_n} \end{bmatrix} = \begin{bmatrix} t_{11}^* & \cdots & t_{1j}^* & \cdots & t_{1n}^* \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{i1}^* & \cdots & t_{ij}^* & \cdots & t_{in}^* \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{n1}^* & \cdots & t_{nj}^* & \cdots & t_{nn}^* \end{bmatrix}. \tag{11}$$

(4) Establishing the unweighted supermatrix W

The total influence-relation matrix T_C^* for the normalized indicators is transposed to gain the unweighted supermatrix W, as indicated in equation (12).

$$W = \left(T_C^*\right)' = \begin{bmatrix} t_{11}^* & \cdots & t_{j1}^* & \cdots & t_{n1}^* \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{1i}^* & \cdots & t_{ji}^* & \cdots & t_{ni}^* \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{1n}^* & \cdots & t_{jn}^* & \cdots & t_{nn}^* \end{bmatrix} = \begin{bmatrix} W_{11} & \cdots & W_{1j} & \cdots & W_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ W_{i1} & \cdots & W_{ij} & \cdots & W_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ W_{n1} & \cdots & W_{nj} & \cdots & W_{nn} \end{bmatrix}. \tag{12}$$

Step 2. Establishing the weighted supermatrix S

The abovementioned total influence-relation matrix for the normalized indicators is transposed to gain the unweighted supermatrix W, and then the total influence-relation matrix for the dimensions received from DEMATEL establishes the weighted supermatrix S. The detailed computing process is explained as below:

(1) Establishing the total influence-relation matrix T_D for the DEMATEL dimensions

The total influence-relation matrix T_D for the dimensions gained from (1) to (4) of DEMATEL is formulated as follows: $T_D = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_D^{i1} & \cdots & t_D^{ij} & \cdots & t_D^{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_D^{n1} & \cdots & t_D^{nj} & \cdots & t_D^{nn} \end{bmatrix}$, where t_D^{ij} denotes the total influence value of Dimension i to Dimension j; n represents the number of dimensions.

(2) Establishing the normalized standard v_i of the total influence-relation matrix T_D for dimensions
The normalized standard of the total influence-relation matrix T_D for dimensions is set as v_i. The normalized standard v_i is to add up the row vectors of Matrix T_D to gain n value (s) of v_i in total, as demonstrated in (13) and (14).

$$T_D = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_D^{i1} & \cdots & t_D^{ij} & \cdots & t_D^{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_D^{n1} & \cdots & t_D^{nj} & \cdots & t_D^{nn} \end{bmatrix}^{v_1=\sum_{j=1}^{n} t_D^{1j}}, \tag{13}$$

$$v_i = \sum_{j=1}^{n} t_D^{ij}. \tag{14}$$

(3) Establishing the total influence-relation matrix T_D^* for the normalized dimensions
The numbers of the total influence-relation matrix T_D^* for the normalized dimensions are gradually divided by the normalized standard v_i of its rows, so that the total influence-relation matrix T_D^* for the normalized dimensions can be established, as seen in equation (15). The normalized standard v_i is displayed in (13) and (14).

$$T_D^* = \begin{bmatrix} \frac{t_D^{11}}{v_1} & \cdots & \frac{t_D^{1j}}{v_1} & \cdots & \frac{t_D^{1n}}{v_1} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{t_D^{i1}}{v_i} & \cdots & \frac{t_{i\,D}^{ij}}{v_i} & \cdots & \frac{t_D^{in}}{v_i} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{t_D^{n1}}{v_n} & \cdots & \frac{t_D^{nj}}{v_n} & \cdots & \frac{t_D^{nn}}{v_n} \end{bmatrix} = \begin{bmatrix} t_{D_{11}}^* & \cdots & t_{D_{1j}}^* & \cdots & t_{D_{1n}}^* \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{D_{i1}}^* & \cdots & t_{D_{ij}}^* & \cdots & t_{D_{in}}^* \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{D_{n1}}^* & \cdots & t_{D_{nj}}^* & \cdots & t_{D_{nn}}^* \end{bmatrix}. \tag{15}$$

(4) Establishing the weighted supermatrix S
After the total influence-relation matrix T_D^* for the normalized dimensions is transposed as the weighting basis of the unweighted matrix W, the correspondent position after the transposition of T_D^* multiplies the unweighted matrix W to establish the weighted supermatrix S, as demonstrated in equation (16).

$$S = W \times \left(T_D^*\right)' = \begin{bmatrix} S_{11} & \cdots & S_{1j}S_{1j} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ S_{i1} & \cdots & S_{ij} & \cdots & S_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nj} & \cdots & S_{nn} \end{bmatrix}. \tag{16}$$

Step 3. Establishing the extreme supermatrix L and the weight of each indicator

By means of the characteristic showing that the sum of all column vectors for the weighted supermatrices is 1, the weighted supermatrices are multiplied by $\lim_{t\longrightarrow\infty} S^t$ plenty of times to achieve convergence and become stable. Thus, the extreme supermatrix L is resulted, and the importance priority for the weights of all indicators is also obtained. The establishment of the extreme supermatrix L is seen in equation (17).

$$\lim_{t\longrightarrow\infty} S^t \tag{17}$$

The term weight in statistical methodology refers to the distribution frequency of a factor in the system, which is usually used to analyze the proportion [29]. As mentioned above, this study adopts the multi-criteria decision-making model of DANP to understand the causality and relevance, and analyze the weights and ranking of importance, thus providing a reference for relevant industries aimed at achieving sustainable operation to use resources when developing affiliated restaurants in a real sense.

4. Results

4.1. DEMATEL Analysis. This paper adopted the DEMATEL analysis. 16 effective questionnaires filled out by the experts were collected, and the DEMATEL method was applied to explore the cause-and-effect relationships and correlations of the affiliated restaurants' core resources as well as impact indicators. This paper referred to the DEMATEL expert questionnaire for core resources and impact indicators of affiliated restaurants' development based on the evaluation scale proposed by Lin and Wu [30]. The evaluation scale contains five levels, including "no impact (0)," "low impact (1)," "middle impact (2)," "high impact (3)," and "extremely high impact (4)."

The experts first judged and evaluated the degree of mutual influence among the projects, after which the data of the expert questionnaire were converted into a matrix, and the total average value of each item in the questionnaire was calculated by the formula (1), thus creating a matrix of average expert opinions on dimensions and indicators of core resources and impact indicators for the development of affiliated restaurants.

Then, the relevance and impact between four dimensions and eight indicators were analyzed to find out the most influential indicator. In addition, the study explored the core resources through equations (2) to (4), and simplified the values less than the threshold of the total impact relationship matrix T to 0. We first obtained a simplified total influence relationship matrix of dimensions and indicators to draw the correlations in the causality diagram, as shown in Tables 2 and 3.

Next, equations (5) and (6) are used to compute the sum of columns and rows. Last, we can gain the result for the degree of correlation $(d+r)$ as well as the degree of cause $(d-r)$, and the computing lists of columns and rows for the total influence-relation matrices of the dimensions and indicators is sorted out, as shown in Tables 4 and 5.

According to Tables 4 and 5, $d+r$ (degree of correlation) represents the vertical axis while $d-r$ (degree of cause) represents the horizontal axis to map the dimension cause-and-effect graphs and indicator cause-and-effect graphs for the core resources and impact indicators of the affiliated restaurants' development, as illustrated in Figures 1 and 2, where $d-r$ can analyze the cause and effect of the cause-and-effect relationship. In addition, according to Tables 2 and 3, the correlations between the core resources and impact indicators of the affiliated restaurants' development can be mapped.

To sum up the previous analysis, this paper uses the DEMATEL to explore the cause-and-effect relationships and correlations for the core resources and impact indicators of the affiliated restaurants' development, as explained as follows:

(1) In the aspect of dimensions: According to the dimension cause-and-effect graph (Figure 1), only the value of $d+r$ for "intangible assets" is larger than the average. Therefore, it can be learned that the indicators and dimensions for the core resources and impact indicators of the affiliated restaurants' development are more independent. Concerning the dimensions of "intangible assets" and "tangible assets," they tend to be easily affected because the value of $d-r$ is smaller than 0, which represents "effect" in the cause-and-effect relationship. However, the dimensions of "personal ability" and "organizational ability" belong to the dimensions of cause because the degree of cause is larger than 0, which represents "cause" in the cause-and-effect relationship. Therefore, it is suggested that the owners who intend to develop affiliated restaurants should emphasize "personal ability" and "organizational ability."

(2) In the aspect of indicators: According to the indicator cause-and-effect graph (Figure 2), "brand/business reputation resources," "organizational resources," "marketing resources," and "human resources" are the indicators whose value of $d+r$ is larger than the average, which means there are more correlations between each other. It is considered that "brand/business reputation resources," "organizational resources," and "physical resources" belong to the indicators which tend to be influenced. Although the degree of correlation for the indicators of "financial resources," "technical resources," and "relationship resources" is not above the average, the degree of cause is larger than 0; they belong to influential indicators. As for "marketing resources" and "Human resources," the degree of correlation is larger than the average and the degree of cause is larger than 0, which means that they are core indicators in the core resources and impact indicators for the affiliated restaurants' development. Hence, it is suggested that the owners who intend to develop affiliated restaurants can place more emphasis on "marketing resources" as well as "human resources," and then on "financial resources," "technical resources," and "relationship resources."

4.2. DANP Weight Analysis. Based on the total impact dimensions and indicators of core resources and impact indicators for the development of affiliated restaurants calculated by using the DEMATEL method, this study conducted a follow-up DANP weight analysis. Firstly, this study, referring to a matrix of average expert opinions on four dimensions and eight indicators, established a total influence relationship matrix of dimensions and indicators according to equation (4). Besides, the sum of the relevant values of each dimension was used as the positive planning benchmark, as shown in Tables 6 and 7.

According to Tables 6 and 7, this paper refers to equation (15) to individually divide the values of the total influence-relation matrices of dimensions and indicators by the values of the normalization standard of each row, so that the total influence-relation matrices of the normalization dimensions and indicators can be established. Next, this paper refers to equation (12) to separately transpose the total influence-relation matrices of the normalization dimensions and indicators, so that the unweighted super matrices will be received, as displayed in Tables 8 and 9.

In addition, this paper uses equation (17) to undertake the calculation of maximization in Table 8, and then the dimension weights of core resources and impact indicators for the affiliated restaurants' development, as revealed in Table 10.

According to the abovementioned, this paper applies equation (16) to multiply the unweighted supermatrices of the correspondent positions in Tables 8 and 9, so that the weighted supermatrices can be established. Last, equation (17) will be referred to help the weighted supermatrices multiply themselves by $\lim_{t\longrightarrow\infty} S^t$ many times to reach convergence, and then create the extreme supermatrices and also obtain weights for each indicator for importance priority, as shown in Table 11.

Table 2: List of simplified total influence relationship matrices of the dimensions.

The simplified total influence-relation matrices of the dimensions	Tangible assets	Intangible assets	Personal ability	Organizational ability
Tangible assets act	0.0000	2.6189	0.0000	0.0000
Intangible assets	2.6086	2.5829	2.5107	2.6312
Personal ability	0.0000	2.7103	0.0000	2.4926
Organizational ability	2.4775	2.7158	0.0000	0.0000

Table 3: List of simplified total influence-relation matrices of the indicators.

The simplified total influence-relation matrices of the indicators	Physical resources	Financial resources	Brand/business reputation resources	Technical resources	Relationship resources	Marketing resources	Human resources	Organizational resources
Physical resources	0.0000	0.0000	0.8754	0.0000	0.0000	0.7765	0.0000	0.7897
Financial resources	0.8017	0.0000	0.8976	0.0000	0.0000	0.8189	0.7824	0.8469
Brand/business reputation resources	0.0000	0.7946	0.7921	0.0000	0.0000	0.8356	0.7847	0.8442
Technical resources	0.0000	0.0000	0.8589	0.0000	0.0000	0.0000	0.0000	0.7926
Relationship resources	0.0000	0.0000	0.8254	0.0000	0.0000	0.0000	0.0000	0.0000
Marketing resources	0.7915	0.7935	0.9414	0.7756	0.0000	0.0000	0.0000	0.8379
Human resources	0.0000	0.7806	0.9345	0.7915	0.0000	0.8195	0.0000	0.8447
Organizational resources	0.7892	0.7970	0.9467	0.7771	0.0000	0.8334	0.8067	0.0000

Table 4: Computing list of columns and rows for the total influence-relation matrices of the dimensions.

Dimensions	Sum of rows	Ranking	Sum of columns	Ranking	$d+r$ (degree of correlation)	Ranking	$d-r$ (degree of cause)	Ranking
Tangible assets	9.4475	4	9.6947	3	19.1422	4	−0.2472	3
Intangible assets	10.3335	1	10.6279	1	20.9614	1	−0.2944	4
Personal ability	9.8365	3	9.4252	4	19.2617	3	0.4113	1
Organizational ability	9.8999	2	9.7695	2	19.6694	2	0.1303	2
Average					19.7587			

Table 5: Computing list of columns and rows for the total influence-relation matrices of the indicators.

Indicators	Sum of rows	Ranking	Sum of columns	Ranking	$d+r$ (degree of correlation)	Ranking	$d-r$ (degree of cause)	Ranking
Physical resources	5.9824	6	5.9836	6	11.9660	6	−0.0013	6
Financial resources	6.3171	4	6.0216	4	12.3386	5	0.2955	2
Brand/business reputation resources	6.3151	5	7.0720	1	13.3871	1	−0.7569	8
Technical resources	5.9329	7	5.9017	7	11.8346	7	0.0311	4
Relationship resources	5.6906	8	5.6769	8	11.3676	8	0.0137	5
Marketing resources	6.3815	2	6.3159	3	12.6975	3	0.0656	3
Human resources	6.3668	3	6.0129	5	12.3796	4	0.3539	1
Organizational resources	6.4405	1	6.4422	2	12.8827	2	−0.0017	7
Average					12.3567			

According to the analysis results of Tables 10 and 11, concerning the core resources and impact indicators for the development of affiliated restaurants, the importance priority of the dimensions is "intangible assets," "organizational ability," "tangible assets," and "personal ability." In addition, the results of Table 11 are shown in the radar analysis diagram (Figure 3), and it is found that the weight priority of four impact indicators—"organizational resources," "human resources," "financial resources," and "physical resources"—is relatively important. Thus, this paper conducts the analysis on the evaluation detailed items of the top four indicators, in order to provide the owners who intend to develop affiliated restaurants for further reference.

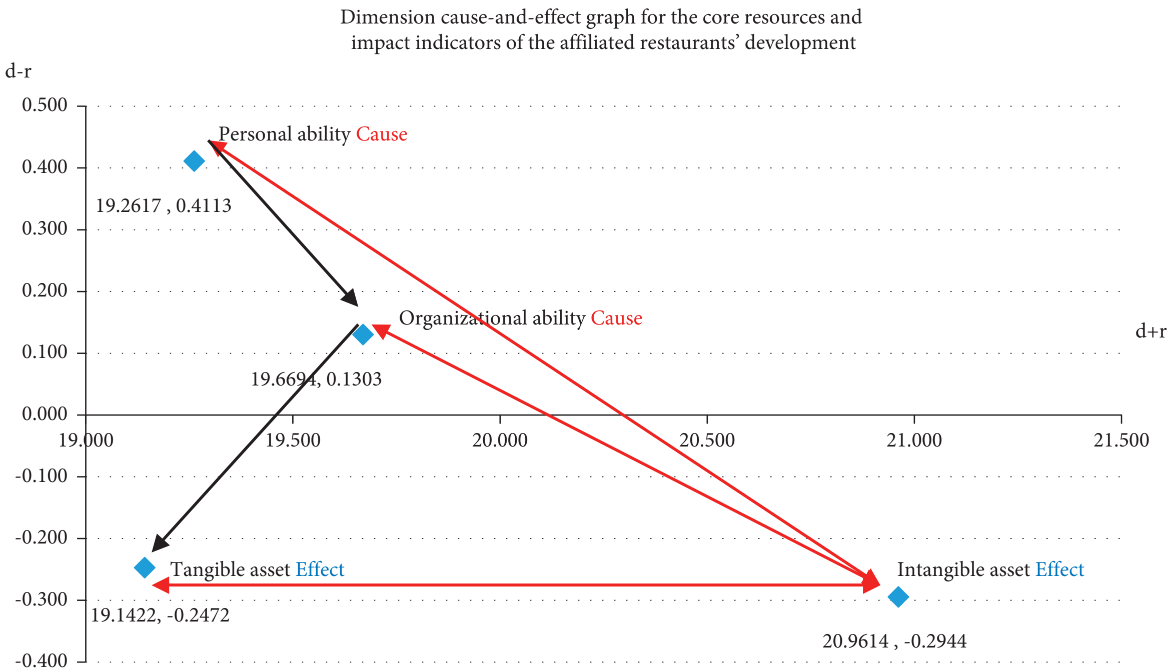


Figure 1: Dimension cause-and-effect graph.

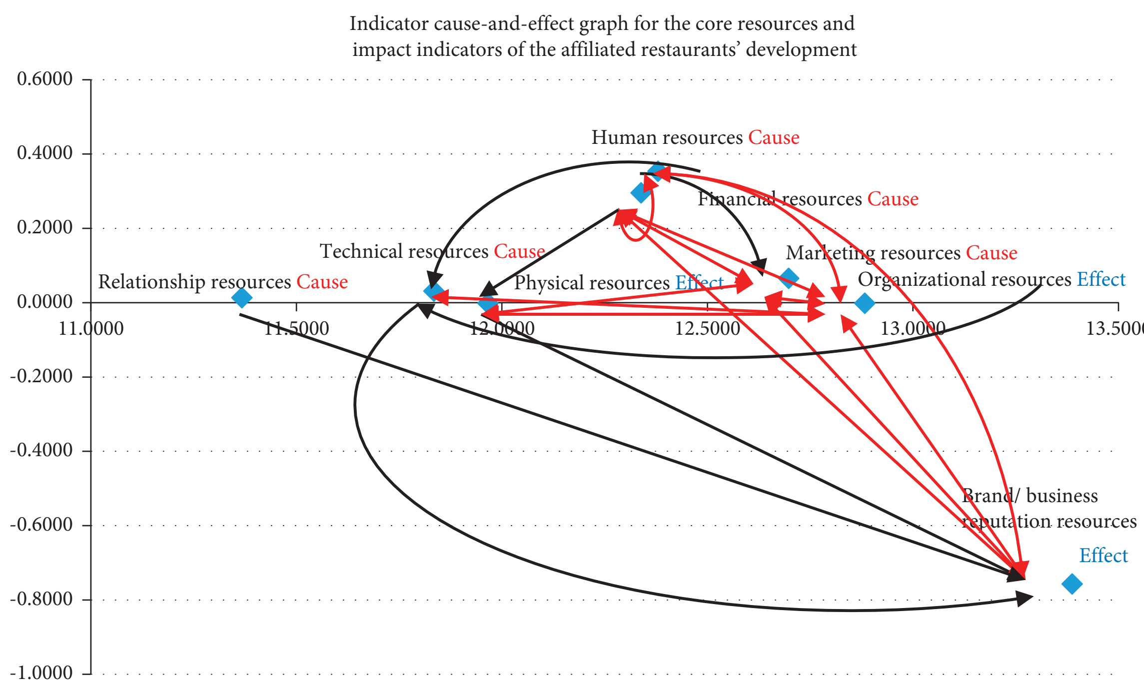


Figure 2: Indicator cause-and-effect graph.

Table 6: Normalization standard list for the total influence-relation matrices of the dimensions.

The total influence-relation matrices of the dimensions	Tangible assets	Intangible assets	Personal ability	Organizational ability	Normalization standard
Tangible assets	2.1559	2.6189	2.3026	2.3701	9.4475
Intangible assets	2.6086	2.5829	2.5107	2.6312	10.3335
Personal ability	2.4527	2.7103	2.1809	2.4926	9.8365
Organizational ability	2.4775	2.7158	2.4310	2.2756	9.8999

Table 7: Normalization standard list for the total influence-relation matrices of the indicators.

f_i	Physical resources	Financial resources	Normalization standard	Brand/ business reputation resources	Technical resources	Relationship resources	Marketing resources	Normalization standard	Human resources	Normalization standard	Organizational resources	Normalization standard
Physical resources	0.6347	0.7472	1.3819	0.8754	0.7261	0.6971	0.7765	3.0751	0.7356	0.7356	0.7897	0.7897
Financial resources	0.8017	0.6744	1.4761	0.8976	0.7643	0.7308	0.8189	3.2116	0.7824	0.7824	0.8469	0.8469
Brand/business reputation resources	0.7711	0.7946	1.5657	0.7921	0.7531	0.7397	0.8356	3.1205	0.7847	0.7847	0.8442	0.8442
Technical resources	0.7299	0.7344	1.4643	0.8589	0.6209	0.6781	0.7678	2.9257	0.7503	0.7503	0.7926	0.7926
Relationship resources	0.6956	0.6999	1.3955	0.8254	0.6930	0.5729	0.7492	2.8405	0.7042	0.7042	0.7505	0.7505
Marketing resources	0.7915	0.7935	1.5851	0.9414	0.7756	0.7568	0.7150	3.1888	0.7698	0.7698	0.8379	0.8379
Human resources	0.7699	0.7806	1.5505	0.9345	0.7915	0.7468	0.8195	3.2924	0.6791	0.6791	0.8447	0.8447
Organizational resources	0.7892	0.7970	1.5861	0.9467	0.7771	0.7547	0.8334	3.3119	0.8067	0.8067	0.7357	0.7357

Table 8: List for the unweighted supermatrices of the dimensions.

The unweighted supermatrices	Tangible assets	Intangible assets	Personal ability	Organizational ability
Tangible assets	0.2282	0.2524	0.2493	0.2503
Intangible assets	0.2772	0.2500	0.2755	0.2743
Personal ability	0.2437	0.2430	0.2217	0.2456
Organizational ability	0.2509	0.2546	0.2534	0.2299

Table 9: List for the unweighted supermatrices of the indicators.

The unweighted supermatrices	Physical resources	Financial resources	Brand/business reputation resources	Technical resources	Relationship resources	Marketing resources	Human resources	Organizational resources
Physical resources	0.4593	0.5431	0.4925	0.4985	0.4985	0.4994	0.4966	0.4975
Financial resources	0.5407	0.4569	0.5075	0.5015	0.5015	0.5006	0.5034	0.5025
Brand/business reputation resources	0.2847	0.2795	0.2538	0.2936	0.2906	0.2952	0.2838	0.2858
Technical resources	0.2361	0.2380	0.2413	0.2122	0.2440	0.2432	0.2404	0.2346
Relationship resources	0.2267	0.2276	0.2370	0.2318	0.2017	0.2373	0.2268	0.2279
Marketing resources	0.2525	0.2550	0.2678	0.2624	0.2638	0.2242	0.2489	0.2516
Human resources	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Organizational resources	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 10: List for dimension weights.

Dimension weights	Tangible assets	Intangible assets	Personal ability	Organizational ability
Tangible assets	0.2452	0.2452	0.2452	0.2452
Intangible assets	0.2688	0.2688	0.2688	0.2688
Personal ability	0.2387	0.2387	0.2387	0.2387
Organizational ability	0.2473	0.2473	0.2473	0.2473

4.2.1. Organizational resources. "Organizational resources" is the most important core indicator. Its five items for evaluation are "organizational culture," "administration and purchasing," "organization and memory learning," "cross-organization cooperation networks," and "organizational creativity and operational specialization." This paper discusses the results with experts of the industry and integrates their suggestions, in order to develop good organizational culture and administration purchasing system for the development of affiliated restaurants, establish organization and memory learning as well as cross-organization cooperation networks, and then enhance the operation team's performance as well as their competiveness by means of the organizational creativity and operational specialization. As a result, the abovementioned five evaluation factors all can be offered to the owners of the affiliated restaurants for reference when getting engaged into the organizational resource allocation.

4.2.2. Human Resources. This paper collects and sorts numerous experts' and scholars' researches as well as the industry experts' suggestions, in order to confirm whether they conform to "human resource allocations and training," "technical skills," "management ability/leadership," and "social networks/communication ability" listed in the evaluation detailed items for human resources of this paper, all of which are the major evaluation detailed items and key points of the human resources which can help the owners for the development of the affiliated restaurants. Among them, the human resource allocations and training can help the organizational members carry out their duties and continue their learning; increase their technical skills and ability; and cultivate interpersonal exchange skills, communication ability, management ability, and leadership, in order to become the most powerful support to improve service quality and build a good organizational system.

4.2.3. Financial and Physical Resources. A sound financial structure, abundant investment funds, and complete corollary equipment are all taken into consideration for the development of affiliated restaurants. Meanwhile, the design of floor plan with theme features and the location of the business base are the main factors that are able to attract consumers' attention. Besides, creativity and environmental protection are the keys of the plan design and theme features of Taiwanese restaurants, while location selection and the average sale per unit area are not only important parts for retail and service industries but also crucial elements for the development of affiliated restaurants. The abovementioned evaluation factors can be referred by the owners when they are considering the physical and financial resource allocations in the aspects of ideology and reality.

Table 11: List for indicator extreme supermatrices.

Dimensions	Evaluation indicators	Physical resources	Financial resources	Brand/business reputation resources	Technical resources	Relationship resources	Marketing resources	Human resources	Organizational resources	Priority
Tangible assets	Physical resources	0.1221	0.1221	0.1221	0.1221	0.1221	0.1221	0.1221	0.1221	4
	Financial resources	0.1231	0.1231	0.1231	0.1231	0.1231	0.1231	0.1231	0.1231	3
Intangible assets	Brand/business reputation resources	0.0762	0.0762	0.0762	0.0762	0.0762	0.0762	0.0762	0.0762	5
	Technical resources	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	7
	Relationship resources	0.0611	0.0611	0.0611	0.0611	0.0611	0.0611	0.0611	0.0611	8
	Marketing resources	0.0678	0.0678	0.0678	0.0678	0.0678	0.0678	0.0678	0.0678	6
Personal ability	Human resources	0.2387	0.2387	0.2387	0.2387	0.2387	0.2387	0.2387	0.2387	2
Organizational ability	Organizational resources	0.2473	0.2473	0.2473	0.2473	0.2473	0.2473	0.2473	0.2473	1

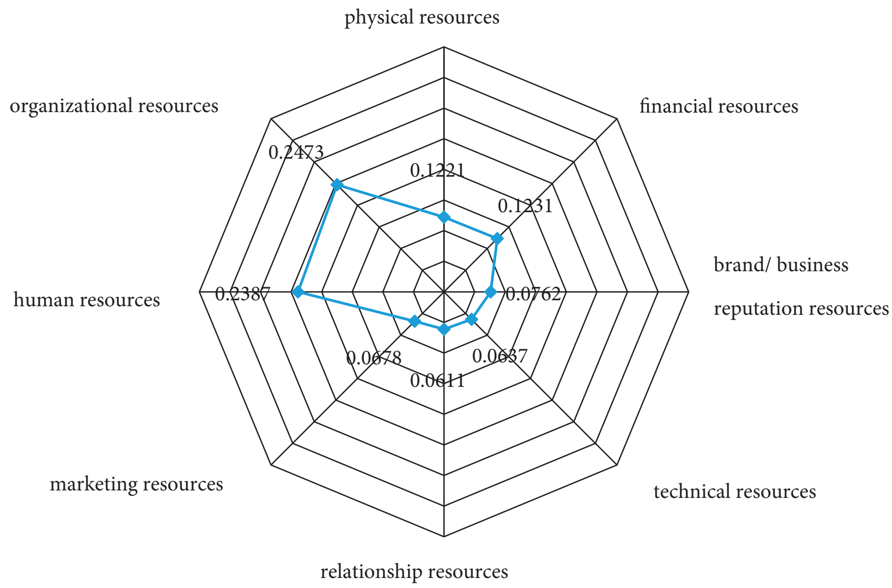


Figure 3: Radar analysis diagram of the core resources and impact indicators for the development of affiliated restaurants.

5. Conclusions and Suggestions

This study aims to explore the innovative business model of the hotel industry, which has a significant influence on the development of the hospitality industry. For Taiwan's tourist hotels, the average catering income is larger than the average rental income. Among the hotels of different levels and general hotels, the hotels with the highest incomes, such as Regent Taipei, all have affiliated restaurants, which is similar to this study's result. Human resources can have an indirect effect on restaurant business performance through the innovative acts [31]. Urbanization has a positive impact on hotel development, such as marketing, image, resources integration, and cooperation intensification [32], which is consistent with the importance of brands and the organizational resources that are emphasized by the major core resources on innovation as well as cross-organizational cooperation for the development of affiliated restaurants in this paper.

In this paper, there are two findings with management implications: one is teamwork which is emphasized in the practice of hotel management, verified by this paper, which discovers organizational resources and human resources as the crucial core resources for the development of affiliated restaurants; the other is the practice of core resource dimensions and indicators which really exist in the affiliated restaurants run by hotels in the practice of hotel business management. In terms of practical influence, in the four core resource dimensions (tangible assets, intangible assets, personal ability, and organizational ability) confirmed by the affiliated restaurants developed by hotels, it is found that both personal ability and organizational ability will affect the applications of tangible assets and intangible assets, personal ability in particular. Moreover, in view of the eight major resource indicators, human resources, financial resources, marketing resources, technical resources, and relationship resources will affect brand indicators, physical indicators, and organizational indicators, in which human resources and financial resources have higher influence and the more influenced indicators are brand indicators.

To sum up, this paper not only conforms to the characteristic of labor intense for the tourism and hospitality industry confirming that human resources predominate the applications and development of other important resources but also discovers that large-medium hotels have more human resources and talents, most of which can use these resources to successfully develop their affiliated restaurants. However, for the hotel industry facing a shortage of talents and personnel, which is becoming more and more serious, there is no doubt that considering how to develop its business of affiliated restaurants and seeking for the sustainable development in the limited resources is an important basis for reference. For future research, (1) It is suggested that different types of affiliated restaurants can be discussed one by one, so as to more accurately confirm the core capabilities and indicators required by various types of restaurants. (2) Further research should be conducted on the major influential indicators, such as human resources, organizational resources, and factors with a high ranking of importance. Regarding research limitations, first, although there were 16 experts in this study, and they were from different universities and hotels, most of them were from northern Taiwan. They may not adequately represent the full spectrum of views held by individuals in different regions across Taiwan. The number and the regions of experts should be taken into consideration in further studies. Second, this study takes Taiwan as the scope of research, and the practices and considerations adopted probably differ from diverse countries.

Data Availability

Data are available on request to the authors. The data source is obtained from the questionnaire analysis of the author's research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] D. Guarascio and F. Tamagni, "Persistence of innovation and patterns of firm growth," *Research Policy*, vol. 48, no. 6, pp. 1493–1512, 2019.

[2] W. E. Souder, "Management relations between R&D and marketing in new product development project," *Journal of Product Innovation Management*, vol. 5, pp. 6–19, 1987.

[3] F. H. Taques, M. G. López, L. F. Basso, and N. Areal, "Indicators used to measure service innovation and manufacturing innovation," *Journal of Innovation and Knowledge*, vol. 6, no. 1, pp. 11–26, 2020.

[4] S. Agarwal, K. Erramilli, and C. S. Dev, "Market orientation and performance in service firms: role of innovation," *Journal of Services Marketing*, vol. 17, no. 1, pp. 68–82, 2003.

[5] Ministry of Economic Affairs, *Operation and Management Practices of the Catering Industry*, The Tenth Division of the Department of Commerce, Ministry of Economic Affairs, Taipei, Taiwan, 2000.

[6] I. Ali, M. Ali, M. A. Salam, Z. A. Bhatti, G. A. Arain, and M. Burhan, "How international SME's vicarious learning may improve their performance? The role of absorptive capacity, strength of ties with local SMEs, and their prior success experiences," *Industrial Marketing Management*, vol. 88, no. 7, pp. 87–100, 2020.

[7] M. Ottenbacher and R. J. Harrington, "The innovation development process of Michelin-starred chefs," *International Journal of Contemporary Hospitality Management*, vol. 19, no. 6, pp. 444–460, 2007.

[8] M. J. Benner and M. Tushman, "Process management and technological innovation: a longitudinal study of the photography and paint industries," *Administrative Science Quarterly*, vol. 47, no. 4, pp. 676–707, 2002.

[9] J. Magretta, "Why business models matter," *Harvard Business Review*, vol. 80, no. 5, pp. 86–93, 2002.

[10] A.-M. Hjalager, "A review of innovation research in tourism," *Tourism Management*, vol. 31, no. 1, pp. 1–12, 2010.

[11] A. Gambardella and A. M. McGahan, "Business-model innovation: general purpose technologies and their implications for industry structure," *Long Range Planning*, vol. 43, no. 2-3, pp. 262–271, 2010.

[12] D. J. Teece, "Business model, business strategy and innovation," *Long Range Planning*, vol. 43, no. 2-3, pp. 172–194, 2010.

[13] H. Chesbrough, "Business model innovation: opportunities and barriers," *Long Range Planning*, vol. 43, no. 2-3, pp. 354–363, 2010.

[14] R. Amit and C. Zott, "Value creation in e-business," *Strategic Management Journal*, vol. 22, no. 6-7, pp. 493–520, 2001.

[15] S. Cavalcante, P. Kesting, and J. Ulhøi, "Business model dynamics and innovation: (re)Establishing the missing linkages," *Management Decision*, vol. 49, no. 8, pp. 1327–1342, 2011.

[16] H. F. Chang, S. H. Wu, J. H. Y. Chen, and C. H. Ke, "Evaluating business model for hotel industry by grey-TOPSIS," *Journal of Risk and Financial Management*, vol. 14, no. 12, pp. 2–12, 2021.

[17] J. J. Yang, H. W. Lo, C. S. Chao, C. C. Shen, and C. C. Yang, "Establishing a sustainable sports tourism evaluation framework with a hybrid multi-criteria decision-making model to explor potential sports tourism attractions in taiwan," *Sustainability*, vol. 12, no. 4, 2020.

[18] J. H. Y. Chen, C. H. Wang, and H. F. Chang, "The study on the core resources and evaluation indicators of affiliated restaurant development for tourist hotels," *Journal of Hospitality and Tourism*, vol. 14, no. 4, pp. 223–249, 2017.

[19] R. Brown, "Managing the 'S' curves of innovation," *Journal of Consumer Marketing*, vol. 9, no. 1, pp. 61–72, 1992.

[20] J. J. P. Jansen, F. A. J. Van Den Bosch, H. W. Volberda, and H. W. Volberda, "Managing potential and realized absorptive capacity: how do organizational antecedents matter?" *Academy of Management Journal*, vol. 48, no. 6, pp. 999–1015, 2005.

[21] J. Tidd, J. R. Bessant, and K. Pavitt, *Managing Innovation: Integrating Technological, Market and Organizational Change*, John Wiley & Sons, NJ, USA, 1997.

[22] A. Johne and R. Davies, "Innovation in medium-sized insurance companies: how marketing adds value," *International Journal of Bank Marketing*, vol. 18, no. 1, pp. 6–14, 2000.

[23] S. A. Zahra, "Technology strategy and financial performance: examining the moderating role of the firm's competitive environment," *Journal of Business Venturing*, vol. 11, no. 3, pp. 189–219, 1996.

[24] C. W. L. Hill and G. R. Jones, *Strategic Management Theory: An Integrated Approach*, Houghton Mifflin Company, MA, USA, 6 edition, 2004.

[25] F. Ludeke-Freund, S. Schaltegger, and K. Dembek, "Strategies and drivers of sustainable business model innovation," in *Handbook of Sustainable Innovation*, F. Boons and A. McMeekin, Eds., Edward Elgar Publishing, Cheltenham, UK, pp. 101–123, 2019.

[26] M. Geissdoerfer, P. Savaget, and S. Evans, "The Cambridge business model innovation process," *Procedia Manufacturing*, vol. 8, pp. 262–269, 2017.

[27] S. Holliday, P. Sherchan, and S. Ebrahimi, *COVID-19 and the Insurance Industry: Why a Gender-Sensitive Response Matters*, International Finance Corporation, Washington, D.C., USA, 2020.

[28] C. H. Wang, "An intuitionistic fuzzy set-based hybrid approach to the innovative design evaluation mode for green products," *Advances in Mechanical Engineering*, vol. 8, no. 4, pp. 1–16, 2016.

[29] K. S. Chen, C. H. Wang, K. H. Tan, and S. F. Chiu, "Developing one-sided specification six-sigma fuzzy quality index and testing model to measure the process performance of fuzzy information," *International Journal of Production Economics*, vol. 208, pp. 560–565, 2019.

[30] C. T. Lin and C. S. Wu, "Selecting a marketing strategy for private hotels in taiwan using the analytic hierarchy process," *Service Industries Journal*, vol. 28, no. 8, pp. 1077–1091, 2008.

[31] C. Lee, R. Hallak, and S. R. Sardeshmukh, "Innovation, entrepreneurship, and restaurant performance: a higher-order structural model," *Tourism Management*, vol. 53, pp. 215–228, 2016.

[32] J. M. Luo and C. F. Lam, "A qualitative study of urbanization effects on hotel development," *Journal of Hospitality and Tourism Management*, vol. 29, pp. 135–142, 2016.

Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 8513719, 17 pages
https://doi.org/10.1155/2022/8513719

Research Article

Hyperparameter Tuning of Machine Learning Algorithms Using Response Surface Methodology: A Case Study of ANN, SVM, and DBN

Warut Pannakkong,[1] Kwanluck Thiwa-Anont,[1] Kasidit Singthong,[1] Parthana Parthanadee,[2] and Jirachai Buddhakulsomsiri[1]

[1]*School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, Thailand*
[2]*Department of Agro-Industrial Technology, Faculty of Agro-Industry, Kasetsart University, Thailand*

Correspondence should be addressed to Jirachai Buddhakulsomsiri; jirachai@siit.tu.ac.th

Received 14 June 2021; Revised 29 November 2021; Accepted 27 December 2021; Published 17 January 2022

Academic Editor: Kuei-Hu Chang

This study applies response surface methodology (RSM) to the hyperparameter fine-tuning of three machine learning (ML) algorithms: artificial neural network (ANN), support vector machine (SVM), and deep belief network (DBN). The purpose is to demonstrate RSM effectiveness in maintaining ML algorithm performance while reducing the number of runs required to reach effective hyperparameter settings in comparison with the commonly used grid search (GS). The ML algorithms are applied to a case study dataset from a food producer in Thailand. The objective is to predict a raw material quality measured on a numerical scale. *K*-fold cross-validation is performed to ensure that the ML algorithm performance is robust to the data partitioning process in the training, validation, and testing sets. The mean absolute error (MAE) of the validation set is used as the prediction accuracy measurement. The reliability of the hyperparameter values from GS and RSM is evaluated using confirmation runs. Statistical analysis shows that (1) the prediction accuracy of the three ML algorithms tuned by GS and RSM is similar, (2) hyperparameter settings from GS are 80% reliable for ANN and DBN, and settings from RSM are 90% and 100% reliable for ANN and DBN, respectively, and (3) savings in the number of runs required by RSM over GS are 97.79%, 97.81%, and 80.69% for ANN, SVM, and DBN, respectively.

1. Introduction

Nowadays, machine learning (ML) algorithms have become an important part of various industries. ML algorithms provide a significant capability to perform or facilitate various tasks. In manufacturing, a company can gain some benefits from ML in terms of performance and efficiency in a wide variety of aspects. For example, ML can be used to reduce the labor cost, human error, and number of product defects or to increase the production rate. Another advantage is that ML algorithms can handle a large amount of input data for model training [1]. The main reason for ML algorithms' growing use is that ML algorithms can improve productivity and efficiency by automating them in the usage environment [1, 2]. Also, ML algorithms can learn from previous experience by discovering patterns in existing data and using those patterns to develop and/or improve their knowledge over time [3]. These benefits of ML algorithms can lead to business revenue and growth.

There are various tasks that ML algorithms can perform. Among them, the most common tasks are classification, clustering, and prediction [4]. Classification is supervised learning that involves predicting or labeling a data class. Training an ML algorithm for classification requires an input dataset with predefined classes. Clustering, an unsupervised machine learning task, involves grouping data into an unknown number of clusters according to some common aspects. Prediction involves estimating some quantitative (numerical) label of future observations by using a mathematical or empirical model. Due to the highly competitive environment of today's business, an accurate prediction model is needed to support the decision-making process, which impacts the business performance. Prediction is used in a wide range of applications today. To select a prediction model, its accuracy is one of the most important criteria for a modeler. For ML algorithms, an important issue in constructing effective prediction models is that the hyperparameters of the algorithms must be appropriately set [5, 6].

Hyperparameter settings are a prespecified set of decisions for ML models that directly affect the training process and the prediction result, which reflects an ML's model performance [6, 7]. Model training is a learning process so that a model can recognize patterns in the training data and predict the output of new data based on these patterns. In addition to hyperparameter setting, model architecture, which indicates the complexity of the model, would also directly impact the execution time to train and test a model. Due to their impacts on the model performance and that the best set of values is unknown, hyperparameter setting has become an important and challenging problem in ML algorithm usage. In the literature, there are several methods for tuning hyperparameters. These methods are briefly discussed below.

Every hyperparameter has a wide range of values for a modeler to select. Without using an efficient tuning strategy, simple approaches are to use the default hyperparameter values suggested by an ML algorithm developer or the recommended values from other research studies in the literature. Also, a manual search can be performed, or values based on the modeler's experience can be used [5, 8]. While using default values and suggested values from previous studies require little effort for hyperparameter tuning, these values may not perform well on different sets of input data [5]. This is because every ML algorithm, when it is applied to a specific dataset, has its own best set of hyperparameter values that may change upon different or updated input data [6, 7, 9, 10]. Therefore, most researchers state that ML algorithms are more effective if their hyperparameters have been tuned [11].

In addition, using values based on a modeler's expertise requires the modeler to have some practical experience in using particular ML algorithms and that the modeler possesses enough knowledge of the application in consideration. In most cases, these requirements are difficult to fulfill. Therefore, efficient and systematic step-by-step tuning strategies that even an inexperienced modeler can follow are clearly more desirable than depending on the modeler's experience.

A sophisticated approach is to find optimal hyperparameter settings for the learning process of the ML algorithms using some optimization techniques. This approach treats hyperparameter setting as an optimization problem, where the objective function is to maximize the ML algorithm performance, i.e., minimizing the errors from ML algorithms, while treating hyperparameters as decision variables. Examples of these methods are genetic algorithm (GA) [11–16], particle swarm optimization (PSO) [17–19], Bayesian optimization [18, 20–22]. Although this approach can yield high ML algorithm performance, such optimization or search algorithms can be difficult to use and may not be available to inexperienced modelers.

Many recent studies propose various techniques to find the set of optimal hyperparameters. These include grid search (GS) [23], random search (RS) [8], or Latin hypercube sampling. Among them, GS is simple, easy to use, and requires little experience from the modeler [8, 11, 12]. With GS, all possible combinations of hyperparameter values are tested to find the best settings based on the specified lower and upper bounds of each hyperparameter, along with a specified step size that forms the hyperparameter space [11].

Since GS executes all possible combinations, many research articles regard this method as an exhaustive search. A weakness of GS is that the combination of hyperparameters increases multiplicatively as the number of hyperparameters increases. This makes GS extremely time-consuming and requires a high computational cost [11–13, 19, 24, 25]. In most situations with limited computational resources, GS may not be an appropriate technique for hyperparameter setting because of its computational requirements.

In addition to the inefficiency of GS, another issue of using GS is that for some ML algorithms, e.g., artificial neural network (ANN) and deep belief network (DBN), rerunning the algorithms with the same hyperparameter settings yields different prediction results. This implies that the best hyperparameter settings found from performing GS one time are likely different from the best hyperparameter settings from another round of GS. This uncertainty is caused by the nature of the ML algorithms. In this study, we refer to this issue as the reliability of hyperparameter setting. To obtain reliable hyperparameter settings, some studies implement k-fold cross-validation as a means to protect against randomness in the ML training process. Moreover, the k-fold cross-validation can also avoid the bias in data separation (i.e., training, validation, and test sets).

An alternative to GS is to perform a random search (RS), which randomly selects the values of hyperparameters [8, 18, 19]. Based on the principle that among a large number of hyperparameters, there are only a few important tunable ones, and RS has been shown to perform better than GS by testing some ML algorithms on some datasets [8]. However, applying this finding to other ML algorithms, applications, and datasets may be speculative.

To overcome the inefficiency of GS, designs of experiment (DOE) techniques have been proposed to find the optimal hyperparameter values of ML algorithms [7, 26, 27]. DOE is a mathematical and statistical approach, which is used to evaluate the effects of multiple experimental factors at the same time. DOE involves planning a series of experiments for hyperparameter testing, where each experiment is a set of experimental runs at different values of hyperparameters that should be tested together. After the experiments are run, a statistical analysis of experimental data is performed to estimate the effects of the hyperparameters on the performance of the ML algorithms. In other words, an empirical model is constructed that relates the performance of ML algorithms, e.g., prediction errors (as response variable) to hyperparameters (as predictors of ML performance). Analyzing the results from an experiment can identify significant factors and their interactions, leading to subsequent experiments that should be run [28, 29]. Some important designs include factorial experiments for a small number of hyperparameters, fractional factorial experiments for a larger number of hyperparameters (up to 15), and response surface methodology (RSM) for numerical hyperparameters [7]. RSM is an efficient technique in DOE that can be used for optimizing the values of hyperparameters [30]. By using RSM, optimal (or near-optimal) settings can be found with a small number of runs [31]. This is because RSM can provide information on an effective search path that can move toward the optimal region [32].

In this study, we propose using RSM with *k*-fold cross-validation to search for optimal (or near-optimal) hyperparameters of ML algorithms. We hypothesize that RSM is similar to GS in terms of ML performance and can give reliable hyperparameter settings. It is also more efficient in terms of the number of experimental runs. Both GS and RSM are performed to find the set of optimal hyperparameters of the three ML prediction models, ANN, support vector machine (SVM), and DBN, using a dataset obtained from an industrial user. The ML model performance, including prediction accuracy and the number of runs, is then compared. The contributions of our study are that we demonstrate from extensive testing the following advantages of using RSM: (1) the approach is applicable to important ML algorithms with numerical hyperparameters, and their infrastructure is specified by the number of neurons in the hidden layer, which is also a numerical factor, (2) it is a step-by-step procedure that does not depend on the ML modeler's experience and knowledge in hyperparameter setting.

2. Problem Statement

This article demonstrates the process of hyperparameter tuning using RSM for ML algorithms for predicting a numerical response variable. The tuning process is a sequential experimentation, consisting of designing a set of initial experiments and experimental data analysis, leading to subsequent experiments. The process continues until an optimal (or near-optimal) set of hyperparameter values is obtained. The hyperparameter tuning process using RSM is also compared with grid search (GS) for the ML algorithm performance, a number of experimental runs, and computational time. Both techniques are applied with three different ML algorithms: an artificial neural network (ANN), support vector machine (SVM), and deep belief network (DBN). Descriptions of the algorithms are briefly discussed next.

2.1. Artificial Neural Network (ANN). Artificial neural network (ANN) was originated in 1943 by McCulloch and Pitts [33]. They proposed an ANN in terms of a mathematical model imitating the brain's neuron connections. A feed-forward neural network (FFNN), a well-known and widely used neural network, has a structure that usually consists of three types of layers: input, hidden, and output layers. The feed-forward term represents one-way direction information flow from the input layer to the output layer. Each node is connected with the other nodes in the different layers by weights.

The learning mechanism of FFNN is the back-propagation algorithm, as shown in Figure 1. The weights and the biases are changed by recommendations from the gradient descent algorithm. The number of cycles that the weights and biases are optimized is called the training cycles [34, 35].

The hyperparameters of FFNN are the numbers of input nodes, numbers of hidden layers and their respective hidden nodes, learning rate, and training cycles. A greater number of layers and nodes can capture more complex relationships between inputs and an output; however, this requires a time-consuming training process. In addition, more complex relationships need a smaller learning rate and greater training cycles, and vice versa. The duration of the training process is proportional to the training cycles.

2.2. Support Vector Machine (SVM). Support vector machine (SVM) was introduced by Vapnik in 1995 [36]. SVM is a supervised ML algorithm for classification and regression problems in various industries such as medicine, banking, beverages, and traffic flow [37–39] because it promises outstanding performance and avoids the overfitting problem that can occur in an ANN.

Originally, SVM could only handle linear problems as it constructs a linear hyperplane to classify the dataset objects. However, nonlinear problems can be analyzed by SVM after data transformation by a kernel function (transformation function). This function is used to transform the points of data to the required form (Figure 2). Nevertheless, the kernel function must be properly selected according to the type of dataset. Otherwise, SVM cannot provide an accurate prediction [40, 41].

The hyperparameters of SVM are complexity constant (C) and convergence epsilon (Conv). The complexity constant (C) represents the trade-off between minimization of the misclassified observations and margin maximization. The higher the value of C, the narrower the margin that causes less misclassification. Conversely, the lower the value of C, the wider the margin that leads to higher misclassification. The convergence epsilon (Conv) influences the precision on the Karush–Kuhn–Tucker (KKT) condition that is the stopping criteria of the hyperplane optimization. The lower the value of Conv, the more the precision of KKT condition, and the more the iterations of hyperplane optimization.

2.3. Deep Belief Network (DBN). A deep belief network (DBN) was created by Hinton in 2006 [42], which is a combination of an artificial neural network (ANN) and a restricted Boltzmann machine (RBM). DBN can be applied

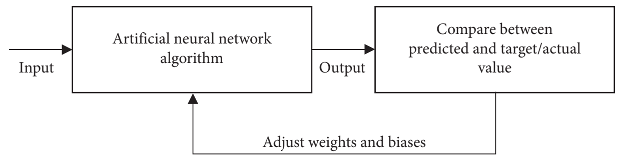


Figure 1: Backpropagation algorithm.

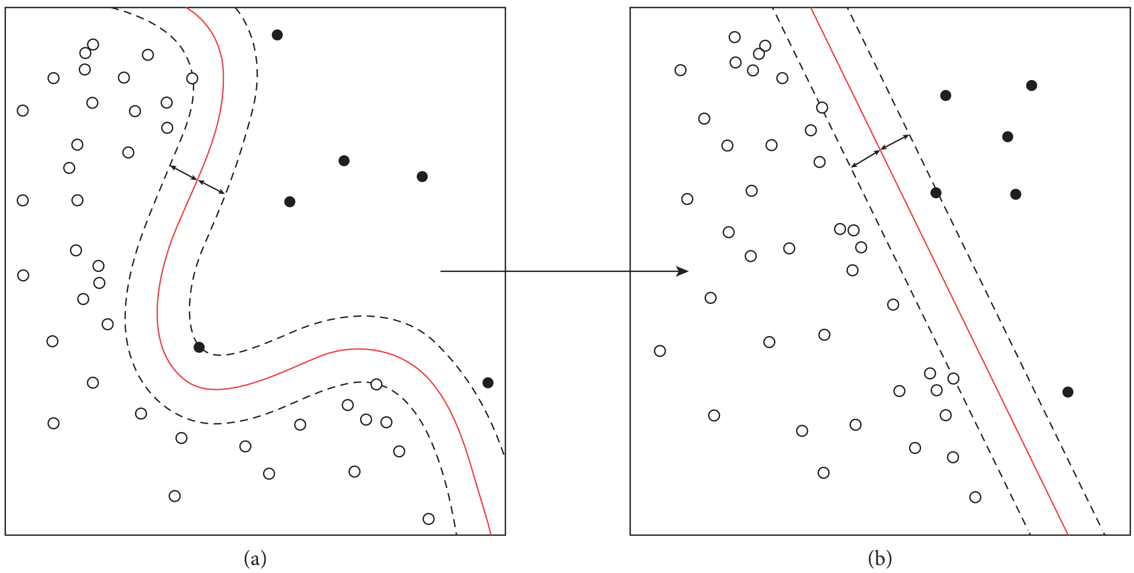


Figure 2: Diagram of (a) SVM with nonlinear hyperplane; (b) SVM with linear hyperplane (source: Alisneaky, 2011).

as a prediction model in various fields (i.e., prediction for reservoir landslide displacement and prediction for deformed coal) and some other applications such as image recognition, speech recognition, and clustering. [43, 44].

The structure of a DBN is similar to an ANN, but its initial weights are initialized by RBM in the pretraining stage before the fine-tuning stage (backpropagation algorithm). The weights from RBM can shorten the computational time in the fine-tuning stage because the computational time of the backpropagation algorithm depends on the initial values of connection weights which are randomly defined in a typical ANN.

The hyperparameters of RBM in the pretraining stage are the learning rate and training cycles of RBM. The hyperparameters (same as in ANN) consist of the number of input nodes, a number of hidden layers and their respective hidden nodes, learning rate, and training cycles of the backpropagation algorithm in the fine-tuning stage. Typically, the learning rate of RBM is larger than the backpropagation algorithm, but the number of training cycles of RBM is smaller than the backpropagation algorithm, as RBM uses a greedy algorithm [45]. The architectures of DBN and RBM are shown in Figure 3.

2.4. ML Algorithm Performance Measure. We evaluate and compare the model performance of the two methods for the best hyperparameter settings. This involves using response surface methodology (RSM) and grid search (GS) by comparing the accuracy of the prediction model. In this study, the mean absolute error (MAE) is a key factor to measure and compare the performance between these two approaches. The MAE can be expressed as follows:

$$\text{MAE} = \sum_{i=1}^{N} \frac{|yi - \hat{y}i|}{N}, \tag{1}$$

where y_i and $\hat{y}_i$ denote the actual value and predicted value of observation i, respectively, e_i denotes the prediction error of observation i, and N denotes the total number of observations in the data. The lower the MAE, the better the model performance.

2.5. Data Partitioning and Cross-Validation. In general, constructing an ML model involves the following steps: constructing an initial model, setting the hyperparameter values, and testing the model performance. To perform these steps, an input dataset is usually partitioned into three datasets. These datasets are the training set for initial model construction, validation set for the tuning hyperparameter, and testing set for evaluating the model performance.

In addition, k-fold cross-validation is applied for the data partitioning process. k-fold cross-validation is a widely used technique that is applied to building and testing models in machine learning. This technique randomly splits a dataset into k subsets of the same size. The value of k is specified by the modeler. Each subset takes turn to be in the training, validation, and testing sets. In other words, the training set contains k−2 subsets, and the validation and testing sets require one subset each. For k-fold cross-validation, an ML algorithm is constructed, validated, and tested k times.

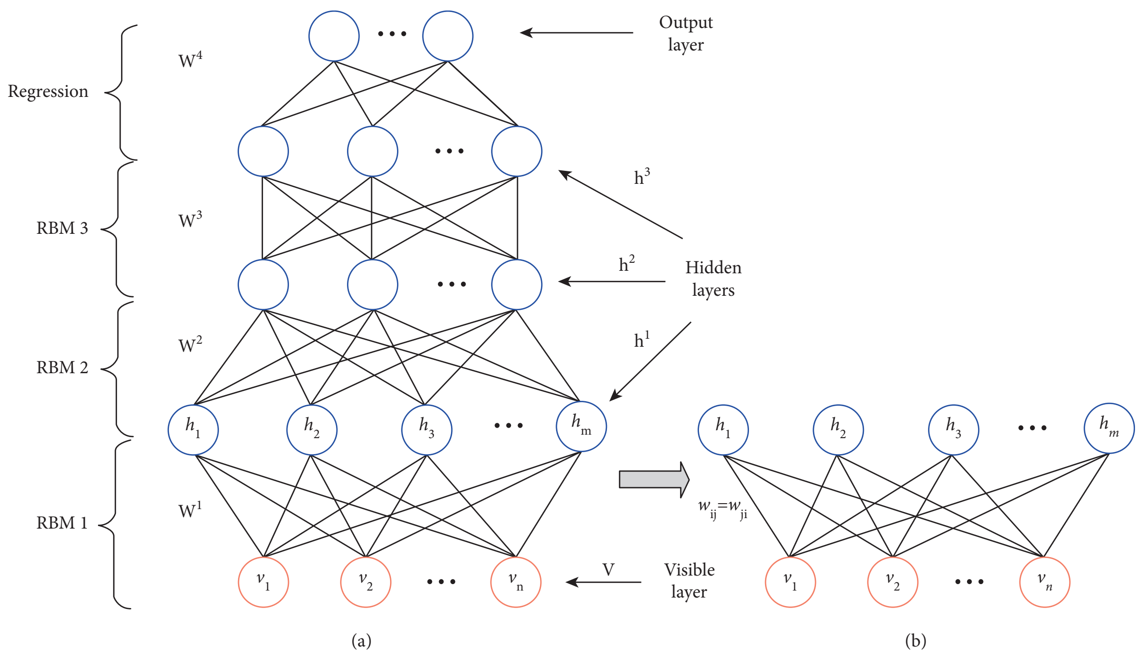


Figure 3: Diagram of (a) deep belief network (DBN) architecture and (b) restricted Boltzmann machines (RBM) (source: Shao et at., 2018).

3. Hyperparameter Tuning with RSM

RSM is a design of experiments (DOE) technique that generates a small number of experimental runs to evaluate the causal effects of experimental factors on a response variable [46]. Experimental data are used to fit a regression model that relates the response variable to the experimental factors. Information from the regression model would guide the search process in subsequent experiments toward the region of factor values that optimize the response variable. For ML algorithms, the response variable is the ML performance measure, i.e., MAE in this study, and experimental factors are the hyperparameters of the ML algorithms. The procedure for using RSM for hyperparameter settings implemented in this study is shown in Figure 4.

In Step 1, a list of hyperparameters and their ranges is specified for each ML algorithm. Then, in Step 2, an experiment is designed to generate a number of experimental runs. Each run consists of a set of hyperparameter values that are used to construct the ML model in Step 3, where the prediction performance of the ML model is measured for the training, validation, and test sets. In Step 4, the regression model that relates the prediction performance to the hyperparameters is fitted. For fine-tuning, only the prediction performance of the validation set is used in this step. If the regression model contains only significant linear terms, then the tuning process has not reached the optimal region of hyperparameters. In this case, the path of steepest descent that would improve the ML model performance is from the coefficients of the variables representing the hyperparameters in the regression model. Subsequent experiments that move the hyperparameter values along this path are run until no further improvement can be obtained (then, go to Step 2). However, if the regression model is a second-order model, then the regression model is optimized to find a set of optimal hyperparameter values. Finally, some confirmation runs are performed to verify the ML model performance at the optimal settings.

In this study, the experimental design that is applied in Step 2 is the central composite design (CCD). The CCD is an efficient design commonly used for constructing a quadratic (second-order) model. Using the CCD, a small number of experiments are performed to optimize the response variable. A CCD generally contains three levels of each factor, as shown in Figure 5. The three types of design points are the factorial points (± 1) or corner points, axial points ($\pm\alpha$), and some replications of the center points (0).

From Figure 5, each factor in a CCD has five levels. Two levels are associated with factorial points, two levels with axial points, and one level at the center. A design space, bounded by factorial points and axial points, is the region of hyperparameters under study. The design space that contains a second-order model of the response variable is the region that has the minimum, maximum, or saddle point.

For each factor, factorial points are low and high values of interest for the factor. Axial points are design points that set all factors at the center, except for one factor. With axial points, a quadratic model of the response variable can be constructed, and the curvature effects of experimental factors can be estimated [30,47]. Setting axial points requires the modeler to set an alpha (α) value. This value is the distance between each axial point and the center point. In this study, the α value is specified as 1.682 for a three-factor experiment (ANN), and 1.414 and 2.378 for a two-factor experiment (SVM) and a six-factor experiment (DBN), respectively. The value of α, which mainly depends on the number of factors, can be found using the following equation:

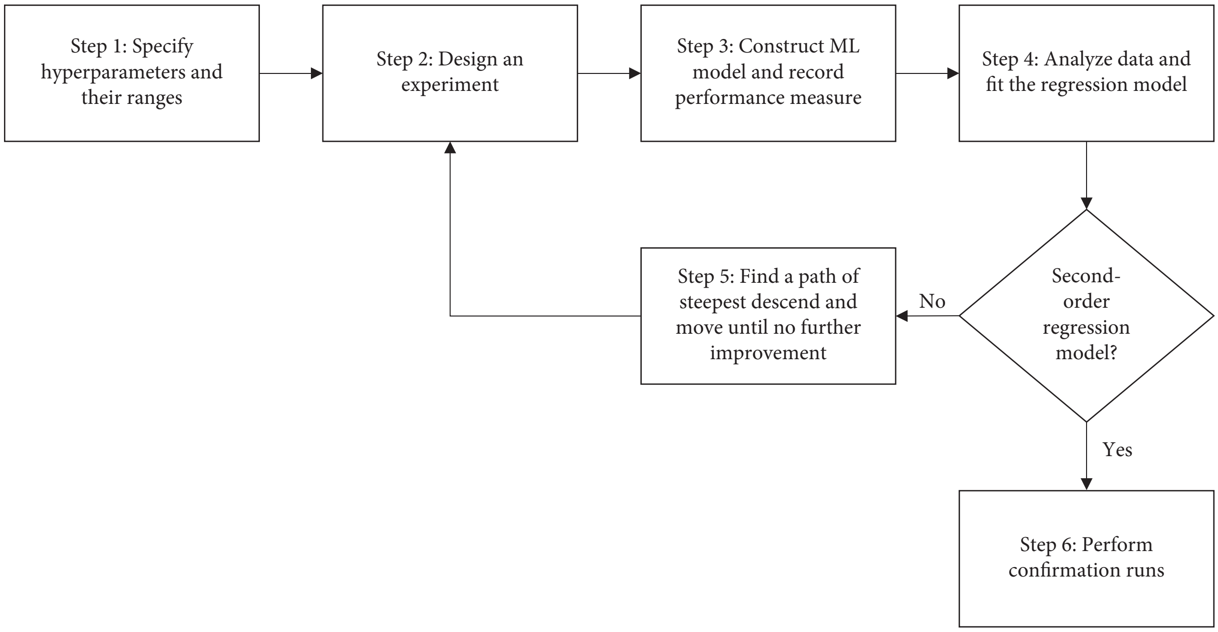


Figure 4: General procedure of RSM.

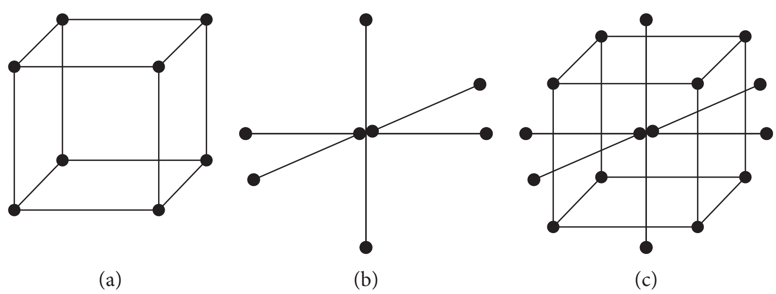


Figure 5: Central composite design (CCD) with three factors: (a) factorial points, (b) axial points and center points, and (c) central composite design.

$$\alpha = [\text{number of experimental runs}]^{1/4}. \quad (2)$$

For the center points, the value is set halfway between the low and high levels of each factor. Replications at the center point are usually performed to provide a measure of the variability of the prediction model, as well as to check for the curvature of the response surface.

In this study, the total number of experimental runs of each ML algorithm depends on the number of hyperparameters. For two-factor CCD (the number of hyperparameters $k = 2$ for SVM), there are $2^k = 4$ factorial points (full factorial), $2k = 4$ axial points, and usually five replications at the center point, for a total of 13 design points for each kernel function. For three-factor CCD ($k = 3$ for ANN), there are 20 design points: $2^k = 8$ factorial points (full factorial), $2^k = 6$ axial points, and six replications of center points. For six-factor half-fraction CCD ($k = 6$ for DBN), there are a total of 53 runs, which are $2^{k-1} = 32$ factorial points (half fraction of a full factorial), $2k = 12$ axial points, and nine center points. In comparison, the number of runs for two-factor, three-factor, and six-factor experiments by GS, with five levels in each factor, is $5^2 = 25$ runs, $5^3 = 125$ runs, and a prohibitive $5^6 = 15,625$ runs, respectively. It can be seen that the CCD offers significant savings in the number of experimental runs when compared to GS. Specifically, a general k-factor CCD contains 2^k factorial points, $2k$ axial points, and n replications at the center, for a total of $(2^k + 2k + n)$ runs, rather than the 5^k runs in GS.

4. Computational Experiment

4.1. Industrial Application and Dataset. A computational experiment is conducted on a dataset obtained from an industrial user, the largest producer and distributor in the canned fruit industry in Thailand. The data are collected at the raw material (RM) receiving operation from one of the main products. This operation is located at the beginning of the production line. The dataset contains observational data over a period of one year from over two thousand batches of RM.

To the user, an important characteristic of the packing medium, which must be prepared in advance, is that it has to match the degree of Brix of the incoming RM. The degree of Brix is, therefore, the dependent variable, of which an accurate prediction would lead to significantly less packing medium preparation cost and lead time. A number of factors can be observed before the arriving RMs are put into production including RM harvest month, color, geographical variables, supplier, and source data. These factors are used as independent variables in the ML prediction models. The dataset is partitioned into 10 subsets for cross-validation purposes, where eight subsets are used as the training set and one subset each as the validation and test sets.

4.2. Hyperparameter Ranges for GS. First, the list of hyperparameters for the three ML algorithms is given in Table 1, along with their initial input ranges. All experimental runs are based on this information.

ANN hyperparameters include the number of hidden nodes (HN), number of training cycles (TC), and learning rate (LR). Using GS, the value of each hyperparameter starts at its lower bound and increases with a fixed step size until reaching the upper bound. With the given number of steps, the total number of experimental runs from GS with 10-fold cross-validation is $(10 \times 21 \times 21 \times 10) = 44{,}100$ runs.

The SVM contains two hyperparameters, which are the complexity constant and convergence epsilon. In addition, a user can specify the type of kernel function of SVM, so it is also treated as a factor in our experiment. Four types of kernel functions are considered, including ANOVA, dot, radial, and Epanechnikov. For SVM, the total number of experimental runs from GS with 10-fold cross-validation is $(102 \times 11 \times 4 \times 10) = 44{,}880$ runs.

For DBN, the hyperparameters include the number of hidden nodes (HN), number of training cycles during pretraining (n_i) and training (n), learning rate of pretraining and training (LR_{RBM} and LR, respectively), and batch size (N_b). Since there are six hyperparameters, the number of steps for each hyperparameter is set to 3, and the total number of experimental runs from GS with 10-fold cross-validation is equal to $(3^6 \times 10) = 7{,}290$ runs.

4.3. GS Results. The 10-fold cross-validation requires that all experimental runs for the three ML algorithms are to be performed 10 times. For each fold, the best hyperparameter settings for each algorithm are the one that results in the minimum MAE. Tables 2–4 contain the best sets of hyperparameters from all 10-fold cross-validation results for ANN, SVM, and DBN, respectively.

In the table, the MAEs of the validation dataset of all 10 folds are given. The reported hyperparameter values for each fold represent the best setting among 4,410 experimental runs. The best values of HN and TC can vary from the lower bound to the upper bound, i.e., HN from 2 to 9 and TC from 10 to 1,000 (most are 500 or more). LR is the only hyperparameter where the best values are clustered around the lower bound, from 0.005 to 0.02, with the most frequent value at 0.005. The results suggest that the best and reliable setting of LR is relatively low, while the best values of the HN and TC are inconclusive.

It is important to note that each value of MAE (from cross-validation) is based on one experimental run at their respective settings. Also, rerunning an ANN at the same hyperparameter setting gives different MAE results due to the nature of ANNs. Therefore, to test the reliability of the best settings found from the 10-fold cross-validation, an ANN with each of these settings is rerun as confirmation. The number of confirmation runs is selected such that the 95% confidence interval of the average MAE of the confirmation runs is within 5% of the mean, which results in eight confirmation runs.

After performing the confirmation runs, the average MAE of the validation set and its SD are reported for each hyperparameter setting. It was found that the average MAEs from confirmation runs are not as good as the MAEs value obtained from cross-validation GS due to the natural variability of the ML algorithm performance. As seen in Table 2, the minimum value of MAE (0.95) from the 1st fold of cross-validation is different from the average of the MAE (1.03) from eight confirmation runs. To properly evaluate the reliability of the hyperparameters from GS, we perform "prediction interval (PI) coverage" in this study. The PI coverage uses the half-width of the 95% PI. We define the performance of GS as reliable if the PI coverage is satisfied, i.e., the MAE from one run (cross-validation) is within the half-width of the 95% PI from the average MAE of the confirmation runs. Finally, the PI coverage of the hyperparameter settings found from GS is satisfied in 8 out of 10 folds. This indicates reasonable (80%) reliability of the ANN hyperparameter values found from GS.

Table 3 provides the best hyperparameter settings from 10-fold cross-validation of SVM. In 7 out of 10 folds, setting the kernel function as ANOVA and a low value of the complexity constant (−1 or 1) is reliable, whereas the best coverage values tend to vary. SVM is an ML algorithm based on statistical learning, where performing a rerun of SVM at the same hyperparameter setting would give the same prediction value, i.e., the same prediction performance. Therefore, there is no need to do the confirmation runs.

Table 4 provides DBN results in the same fashion as Table 2. Most of the best hyperparameter settings are an HN of 10 (high value), n_i and n are either 500 or 1000 (medium or high value), LR_{RBM} and LR are either 0.05 or 0.10 (medium or high value), and the batch size is 1,025 (medium value). In 8 out of 10 folds, the PI coverage is satisfied, which indicates 80% reliability of hyperparameter settings of DBN found from GS.

As mentioned earlier, due to GS multiplicative nature, the required number of runs is large especially when k-fold cross-validation is used. For an ANN with three hyperparameters, the 10-fold cross-validation in our testing requires 44,100 runs. The GS search for the ANN is reasonable because each hyperparameter is searched in over 10 steps. However, for a DBN with six hyperparameters, the same level of detial for GS search is prohibited, i.e., more than 10_6 runs for each fold. The same level of detail for GS search is prohibited, i.e., more than 10^6 runs for each fold. That means the search space of GS for DBN is not well explored. In other words, GS may be ineffective for an ML algorithm with many hyperparameters due to computational resource limitations.

Table 1: List of ANN hyperparameters and their ranges.

ML	Hyperparameter	Description	Lower	Upper	No. of steps
ANN	HN	No. of hidden nodes	1	10	10
	TC	No. of training cycles	10	1000	21
	LR	Learning rate	0.0001	0.1	21
SVM	C	Complexity constant	−1	100	102
	Conv	Convergence epsilon	0.001	0.1	11
DBN	HN	No. of hidden nodes	1	10	3
	n_i	No. of pretraining cycles	10	1000	3
	n	No. of training cycles	10	1000	3
	LR_{RBM}	Pretraining learning rate	0.0001	0.1	3
	LR	Learning rate	0.0001	0.1	3
	N_b	Batch size	350	1700	3

Table 2: Best hyperparameter setting and the test performance of ANN.

	Grid search				Confirmation runs			
Fold	HN	TC	LR	MAE (validation)	Avg MAE (validation)	SD of MAE (validation)	95% PI half-width	PI coverage
1	**7**	**604**	**0.005095**	0.9513	1.0543	0.0605	0.1517	Yes
2	6	802	0.005095	1.0333	1.1461	0.0571	0.1432	Yes
3	9	208	0.005095	0.9637	1.0327	0.032	0.0803	Yes
4	9	852	0.005095	0.9743	1.0706	0.0458	0.1149	Yes
5	5	1000	0.005095	0.9621	1.0731	0.0188	0.0472	No
6	3	10	0.01009	0.9569	1.0265	0.0441	0.1106	Yes
7	9	654	0.01009	1.1191	1.1956	0.0431	0.1081	Yes
8	6	505	0.02008	1.0143	1.2014	0.0713	0.1788	No
9	7	951	0.005095	0.9894	1.0938	0.0538	0.1349	Yes
10	2	604	0.015085	1.0633	1.2126	0.0606	0.152	Yes

Bold values indicate the best set of hyperparameters from Grid Search that leads to the minimal MAE (validation).

Table 3: Best hyperparameter setting and the test performance of SVM.

Fold	Kernel function	*C*	Conv	MAE (validation)
1	*ANOVA*	1	0.0109	1.0668
2	*Radial*	3	0.0307	1.1237
3	*ANOVA*	2	0.0703	1.052
4	*Radial*	75	0.001	1.0492
5	*ANOVA*	1	0.1	1.061
6	*Dot*	−1	0.001	0.9971
7	*ANOVA*	1	0.0406	1.1648
8	*ANOVA*	−1	0.0901	1.105
9	*ANOVA*	−1	0.0208	1.0693
10	*ANOVA*	1	0.0802	1.1319

Table 4: Best hyperparameter setting and the test performance of DBN.

	GS						Confirmation runs				
Fold	HN	n_i	n	LR_{RBM}	LR	N_b	MAE (validation)	Avg MAE (validation)	SD of MAE (validation)	95% PI half-width	PI coverage
1	10	1000	505	0.1	0.05005	1025	0.987	1.0369	0.0318	0.0832	Yes
2	10	1000	10	0.05005	0.1	1025	1.0906	1.119	0.0383	0.1002	Yes
3	10	1000	1000	0.05005	0.05005	350	0.9718	1.01	0.0219	0.0573	Yes
4	10	505	505	0.1	0.05005	1025	1.0092	1.0647	0.0352	0.0921	Yes
5	10	505	1000	0.1	0.05005	1700	0.9978	1.0462	0.0456	0.1193	Yes
6	10	1000	10	0.1	0.1	1025	0.9313	1.0063	0.0246	0.0644	No
7	10	505	1000	0.1	0.1	1025	1.112	1.1737	0.038	0.0994	Yes
8	10	505	505	0.1	0.05005	1025	1.0361	1.0736	0.0333	0.0871	Yes
9	10	505	1000	0.1	0.1	1025	0.9893	1.0675	0.0277	0.0725	No
10	5.5	1000	505	0.05005	0.05005	350	1.0446	1.1091	0.0251	0.0657	Yes

4.4. RSM Results

4.4.1. Artificial Neural Network. From the initial ranges of hyperparameters, listed in Table 1, the search process begins at the low values of these hyperparameters, i.e., near the origin point of the hyperparameter space. The lower bound and upper bound are specified for the axial points of the CCD. Since HN and TC are integers, the values of the hyperparameters at factorial points are rounded to the nearest integer.

Experiment 1. Identifying the steepest descent direction

A three-factor CCD with 20 design points is performed for each data fold. Each row in the table represents an experimental run, where point type of 1, −1, and 0 indicates that the experiment is a factorial point, axial point, and center point, respectively. Note that, this CCD is constructed by specifying the axial points for each hyperparameter as follows: 1 and 3 for HN, 10 and 100 for TC, and 0.0001 and 0.001 for LR. Also, the values of HN of some design points are rounded to the nearest integer since HN cannot be a fractional number. The MAEs of the validation set of all 10 folds of data are shown in Table 5.

Analysis of variance (ANOVA) is performed on each data fold separately. The steps in the data analysis of the second fold are described as an example. First, the regression model begins as a full-quadratic model, which contains the main effects, squared terms, and two-factor interaction terms. Then, insignificant terms are eliminated from the regression model, one at a time, until the final model is obtained. The regression model fitting process is conducted, while maintaining the hierarchy of the model, i.e., keeping lower-order term(s) in the presence of a significant higher-order term.

The ANOVA from the final model of the second data fold is shown in Table 6. The linear term and the quadratic term of TC are significant, while the HN and LR effects are not. This may be caused by the ranges of HN and LR being too narrow. Further analysis as shown in Figure 6 suggests that a higher value of HN could reduce the MAE, and a high value of LR may already be effective. Therefore, the search direction of subsequent experiments needs to increase HN and LR, while fixing TC. A similar analysis is performed on the other nine data folds, which results in nine additional ANOVA tables and regression models. After examining the results of all 10 folds, four patterns of hyperparameter effects on the MAE of the validation set are summarized in Table 7, along with a suggested search direction.

We denote a quadratic effect of a hyperparameter as convex if the value of the hyperparameter that is associated with a low value of MAE occurs in the middle of the input range. A concave pattern indicates the opposite hyperparameter effect where low values of MAE occur at the boundaries of the input range. In addition, there are two linear trends, a negative trend and a positive trend, which point to a low value of MAE occurring at the upper bound and lower bound, respectively. These patterns also suggest the search directions. For a convex pattern and linear positive trend, the hyperparameter values remain unchanged at the value that gives the minimum MAE and at the lower bound, respectively, in subsequent experiments. However, for a concave pattern and linear negative trend, the search direction is to increase the hyperparameter value. The search direction is defined by the coded coefficients of the final regression model. For example, the final regression model from the second fold of data is as follows:

$$\begin{aligned} \text{MAE} = {} & 1.1343 - 0.0006\,HN - 0.0085\,TC - 0.0016\,LR \\ & + 0.0050\,TC2. \end{aligned} \tag{3}$$

Based on the coded coefficients in the model, every coded unit increase in HN is associated with (-0.0000/-0.0016) = 2.6667 coded units increase in LR. The 2.6667 coded units have to be transformed to an original scale. Recall that in the original scale, LR = 0.00028 is coded as −1 at the factorial point, and LR = 0.00055 is coded as 0 at the center points. In other words, a coded unit increase is equivalent to (0.00055–0.00028) = 0.00027 units in LR. Therefore, in the steepest descent direction, an increase of 2.6667 coded units becomes a (0.00027 × 2.6667) = 0.000714 increase in LR.

Experiment 2. Searching along the steepest descent direction

Search results along the steepest descent direction are given in Figure 7. From the results, an HN of 8 and LR of 0.0117 seem to be effective. Therefore, these settings become a new center point for the next experiment.

The process of searching along the path of steepest descent is repeated for each data fold. This process stops when the best hyperparameter values on this path are found. These settings become the center point for further experiments.

Experiment 3. Finding optimal setting

For the second data fold, another CCD is conducted. The results are shown in Figure 8.

The regression model fitting process is performed based on the MAE results and hyperparameter values in Figure 8. The ANOVA of the final model is shown in Table 8. The linear terms and quadratic terms of HN and TC are significant, while the LR effects are not significant. The final regression model is then optimized with respect to HN and TC. The best hyperparameter settings from the second data fold are HN = 8, TC = 194, and LR = 0.005095 with the expected value of MAE equal to 1.0900. Similar to the GS, eight confirmation runs are performed.

Experiment 3 is repeated for the other nine data folds. A summary of the results is shown in Table 9. The table contains the best values of the hyperparameters for all 10 folds, the validation MAE at these settings from the experiment, and the results from the confirmation run. In the last column, PI coverage indicates whether or not the 95% prediction intervals of MAE contain the validation MAE from the RSM experiments. The results show that in 9 out of 10 folds, the 95% PIs contain the validation MAE. This indicates a 90% reliability of the hyperparameter values obtained from RSM.

Table 5: Design and experiment results of Experiment 1.

Point type	Hyperparameter			MAE (validation)									
	HN	TC	LR	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5	Fold 6	Fold 7	Fold 8	Fold 9	Fold 10
1	1	28	0.00028	1.1332	1.1465	1.1254	1.0984	1.1071	1.0267	1.2692	1.1173	1.0874	1.1636
1	3	28	0.00028	1.1146	1.1502	1.1334	1.0932	1.0968	1.0202	1.2843	1.1294	1.0979	1.2028
1	1	82	0.00028	1.1271	1.1358	1.094	1.0736	1.0964	0.9994	1.2469	1.1184	1.064	1.1396
1	3	82	0.00028	1.0968	1.1301	1.079	1.076	1.0865	1.0024	1.2377	1.1203	1.0673	1.1515
1	1	28	0.00082	1.1943	1.1355	1.1634	1.0719	1.1013	1.0267	1.2563	1.1192	1.0741	1.1534
1	3	28	0.00082	1.1126	1.1306	1.0735	1.0753	1.0891	1.0202	1.2627	1.1166	1.0633	1.1422
1	1	82	0.00082	1.1785	1.1306	1.1399	1.0815	1.1001	0.9994	1.2433	1.1187	1.0757	1.1393
1	3	82	0.00082	1.1002	1.1338	1.0409	1.0936	1.0576	1.0024	1.2282	1.0857	1.0849	1.1382
−1	1	55	0.00055	1.1568	1.1344	1.1177	1.0728	1.0998	1.0091	1.2498	1.1186	1.0715	1.1446
−1	3	55	0.00055	1.0994	1.128	1.0669	1.0766	1.0821	1.0107	1.2496	1.1102	1.0669	1.1451
−1	2	10	0.00055	1.1334	1.1778	1.1729	1.1257	1.1336	1.0387	1.2884	1.164	1.1121	1.2212
−1	2	100	0.00055	1.0783	1.1275	1.0786	1.1046	1.0868	0.978	1.2232	1.1127	1.0793	1.1793
−1	2	55	0.0001	1.0783	1.1275	1.0786	1.1046	1.0868	0.978	1.2232	1.1127	1.0793	1.1793
−1	2	55	0.001	1.0852	1.1335	1.0873	1.1112	1.0974	0.9773	1.2438	1.1451	1.0833	1.2123
0	2	55	0.00055	1.0925	1.1483	1.1793	1.0804	1.0969	1.0005	1.2511	1.2337	1.1578	1.1438
0	2	55	0.00055	1.0925	1.1303	1.1046	1.1078	1.0865	0.9727	1.2771	1.2183	1.0833	1.1793
0	2	55	0.00055	1.0882	1.1433	1.1025	1.0948	1.0702	0.9904	1.2396	1.1337	1.0675	1.1806
0	2	55	0.00055	1.0947	1.1305	1.0741	1.0839	1.0886	1.0111	1.2367	1.1917	1.0742	1.1373
0	2	55	0.00055	1.2047	1.129	1.107	1.0889	1.1036	0.9756	1.2324	1.109	1.0673	1.143
0	2	55	0.00055	1.0777	1.1529	1.0663	1.09	1.096	0.9768	1.2828	1.1203	1.0822	1.1441

Table 6: Analysis of variance of the second fold.

Source	Df	Adj SS	Adj MS	F-value	*P* value
Model	4	0.001418	0.000355	3.56	0.031
Linear	3	0.001043	0.000348	3.49	0.042
HN	1	0.00001	0.00001	0.1	0.754
TC	1	0.000998	0.000998	10.02	0.006
LR	1	0.000035	0.000035	0.35	0.562
Square	1	0.000375	0.000375	3.77	0.071
TC × TC	1	0.000375	0.000375	3.77	0.071
Error	15	0.001494	0.0001		
Lack-of-fit	10	0.000947	0.000095	0.87	0.606
Pure error	5	0.000547	0.000109		
Total	19	0.002912			

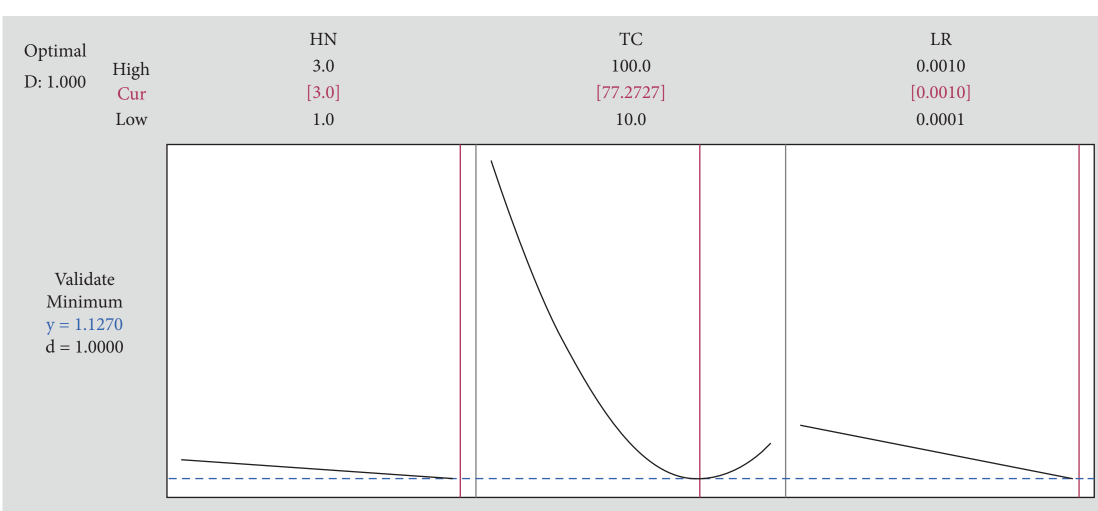


Figure 6: The response optimizer from the second fold.

Table 7: Patterns of hyperparameter effects and search direction.

Fold	Hidden nodes	Training cycles	Learning rate	Search direction
1	Convex	Linear (−)	Linear (+)	Fix HC, TC at minimum MAE and increase TC
2	Linear (−)	Convex	Linear (-)	Increase HN, LR together and fix TC at minimum MAE
3	Convex	Linear (−)	Linear (−)	Fix HN at minimum MAE and increase TC and LR together
4	Concave	Convex	Convex	Increase HN and fix TC
5	Linear (−)	Convex	Linear (−)	Increase HN and LR together
6	Convex	Convex	Linear (−)	Increase LR
7	Linear (−)	Convex	Convex	Increase HN
8	Linear (−)	Linear (−)	Convex	Increase HN and TC
9	Linear (−)	Concave	Linear (+)	Increase HN
10	Concave	Convex	Convex	Increase HN

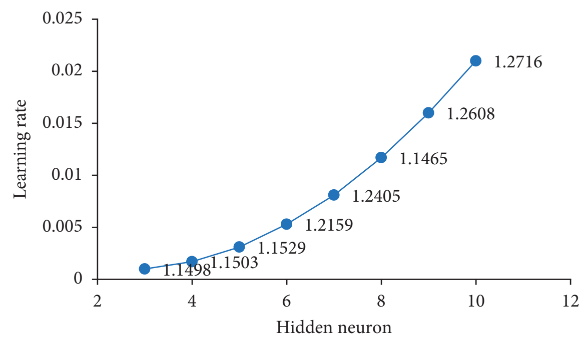


Figure 7: The search direction from the second fold.

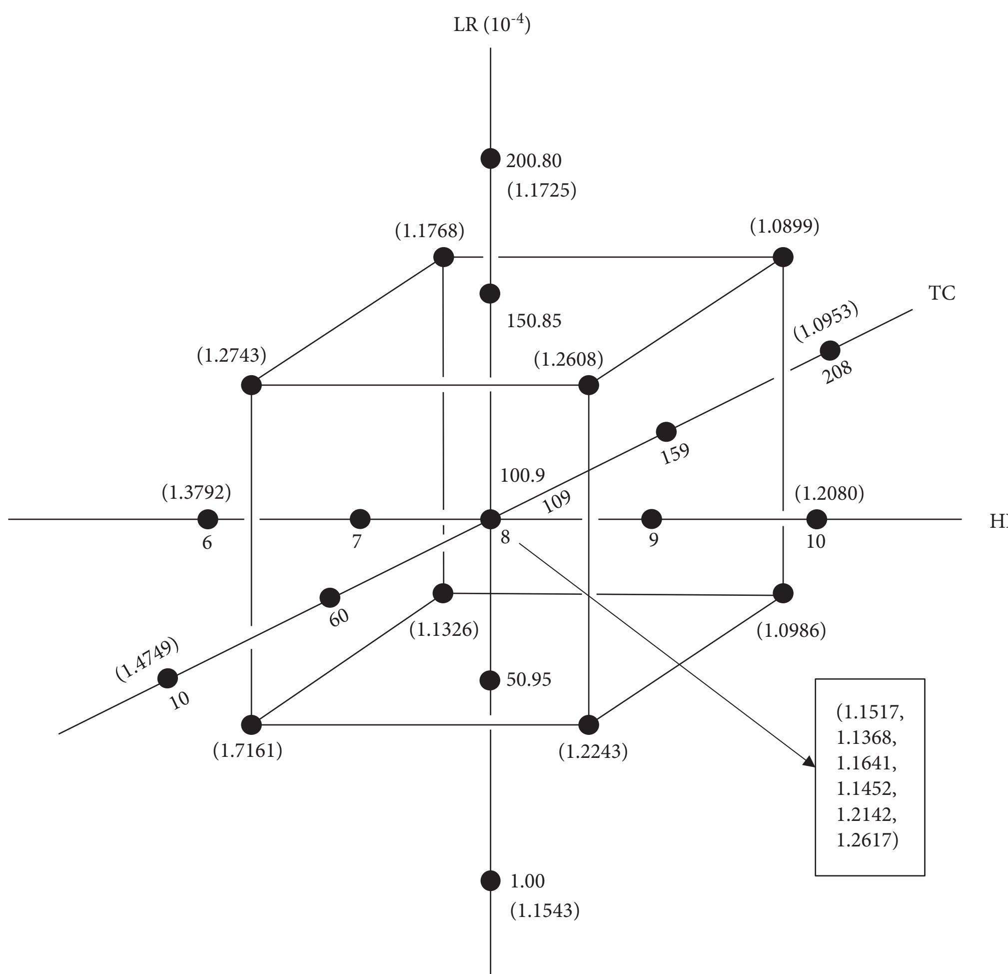


Figure 8: Design and experiment results of Experiment 3.

Table 8: ANOVA of the final model of the second data fold.

Source	Df	Adj SS	Adj MS	F-value	*P* value
Model	4	0.12862	0.032155	10.62	<0.001
HN	1	0.01148	0.011481	3.79	0.070
TC	1	0.08953	0.089534	29.56	<0.001
HN × HN	1	0.01762	0.017617	5.82	0.029
TC × TC	1	0.01483	0.014835	4.9	0.043
Error	15	0.04543	0.003028		
Lack-of-fit	10	0.03347	0.003347	1.4	0.373
Pure error	5	0.01195	0.002391		
Total	19	0.17405			

Table 9: Best hyperparameter setting and the validation performance of ANN using RSM.

			RSM		Confirmation runs			
Fold	HN	TC	LR	MAE (validation)	Avg MA (validation)E	SD of MAE (validation)	95% PI half-width	PI coverage
1	4	802	0.005095	1.012	1.2255	0.0567	0.1422	No
2	8	194	0.005095	1.087	1.1364	0.0503	0.1262	Yes
3	4	951	0.005095	1.034	1.0781	0.0263	0.066	Yes
4	5	258	0.005095	1.095	1.1179	0.0518	0.1299	Yes
5	10	60	0.005095	1.035	1.1535	0.0611	0.1532	Yes
6	**9**	**10**	**0.005095**	**0.98**	1.0818	0.0533	0.1337	Yes
7	5	109	0.005095	1.169	1.2794	0.0675	0.1693	Yes
8	8	456	0.005095	1.062	1.198	0.0643	0.1613	Yes
9	7	208	0.005095	1.051	1.1091	0.0348	0.0873	Yes
10	4	109	0.005095	1.113	1.2119	0.0579	0.1452	Yes

Bold values indicate that this is the combination of hyperparameters that give the minimal average MAE (validation) among all folds.

Among different folds, HN varies from 4 to 10, and TC varies from 10 to 951. The best LR is the same for all folds, which is 0.005095. Although the best settings of HN and TC are inconclusive, it is noticeable that there is a mild trend between HN and TC, i.e., lower HN tends to be associated with higher TC and vice versa.

4.4.2. Support Vector Machine (SVM). Similar to an ANN, the search starts at low values of the initial range of hyperparameter (see Table 1). Since the type of kernel function is a categorical factor, the first experiment is conducted separately for the four types of kernel functions.

Experiment 4. Identifying the steepest descent direction

Using a two-factor CCD, a data fold has 13 experimental runs for each kernel function. The total number of initial experimental runs to find paths of steepest descent is equal to $13 \times 10 \times 4 = 520$ runs. After running all experiments, the results in Table 10 reveal that *dot* and *radial* kernel functions are more effective than *ANOVA* and *Epanechnikov* functions, which, therefore, are not further considered.

The same process of RSM described in the previous section is conducted with SVM. Patterns of hyperparameter effects on MAE for *dot* and *radial* functions are summarized in Table 11, along with the data fold(s) associated with each pattern in the last two columns.

For subsequent experiments, search along the steepest descent direction.

The process of searching along the steepest descent directions to find the appropriate number of steps to move and to find the optimal settings for all 10 folds is performed in the same manner as that of the ANN. Detailed results are omitted to save space. A summary of the optimal hyperparameter settings for all 10 folds is provided in Table 12. Overall, the values of C for dot and radial functions are relatively low, while Conv is inconclusive. As mentioned previously, rerunning SVM at the same settings would give the same prediction value. Therefore, confirmation runs are not performed.

After applying the previous steps to all 10 folds, the best hyperparameters for *dot* and *radial* kernel functions are shown in Table 12. The minimum value of MAE is 1.053 for both kernel functions. For the dot function, the best hyperparameter settings are equal to 9 and 0.0307 for the C and Conv, respectively. For the radial function, C and Conv are 6 and 0.001, respectively.

4.4.3. Deep Belief Network (DBN). The initial ranges of hyperparameters in the first experiment for DBN are listed in Table 1. These ranges are also chosen to start at low values. The lower and upper bounds in Table 11 are values for the axial points. Since HN, *n*, and n_i are integers, their values at factorial points are rounded to the nearest integers.

Experiment 5. : A six-factor half-fraction CCD with 53 design points is performed for each data fold. For 10 folds, a total of $53 \times 10 = 530$ runs are conducted to find the paths of the steepest descent. As an example, ANOVA of the final model from the 2nd data fold is given in Table 13. The obtained regression model provides the steepest descent direction to increase LR together with *n*, while holding the other

Table 10: Experiment 4 results for the four kernel functions.

Kernel function	Average MAE from the validation set									
	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5	Fold 6	Fold 7	Fold 8	Fold 9	Fold 10
ANOVA	1.1964	1.2969	1.1607	1.1763	1.2061	1.2283	1.3041	1.2912	1.2432	1.249
Dot	**1.1021**	**1.1573**	**1.1056**	1.1024	1.1803	**1.0865**	1.32	1.2016	1.2016	1.1701
Radial	1.2124	1.2124	1.1136	**1.0758**	**1.1215**	1.1565	**1.258**	**1.1821**	**1.1479**	**1.1373**
Epanechnikov	1.1963	1.1885	1.1272	1.0887	1.1485	1.1271	1.2944	1.2157	1.1494	1.2193

Bold values indicate the minimal average MAE for each data fold (Fold 1 to Fold 10).

Table 11: Patterns of hyperparameter effects and search direction for *dot* and *radial* kernel function.

C	Conv	Search direction	*dot*	*radial*
Linear (−)	Linear (−)	Increase C and Conv together	Fold: 1, 5, 6, 10	Fold: 1
Concave	Linear (−)	Fix C at minimum MAE and increase Conv	Fold: 2, 7, 9	
Linear (+)	Linear (−)	Fix C at minimum MAE and increase Conv	Fold: 3, 8	
Linear (+)	Linear (+)	Fix C and Conv at minimum MAE	Fold: 4	
Convex	Linear (+)	Fix C and Conv at minimum MAE		Fold: 2
Linear (+)	Linear (-)	Fix C at lower bound and increase Conv		Fold: 3
Concave	Linear (+)	Fix C and Conv at minimum MAE		Fold: 4, 5, 9
Linear (−)	Linear (+)	Increase C and fix Conv at minimum MAE		Fold: 7
Concave	Linear (−)	Fix C at lower bound and increase Conv		Fold: 8, 10

Table 12: Best hyperparameter settings for *dot* and *radial* kernel functions using RSM.

Fold	*Dot*			*Radial*		
	C	Convergence	MAE (validation)	C	Convergence	MAE (validation)
1	12	0.001	1.1680	12	0.0109	1.1455
2	−1	0.1	1.1868	3	0.001	1.1237
3	−1	0.0406	1.1102	−1	0.0703	1.1575
4	-1	0.001	1.1694	**6**	**0.001**	**1.0529**
5	11	0.0109	1.1209	9	0.001	1.1137
6	**9**	**0.0307**	**1.0528**	17	0.0208	1.0892
7	−1	0.1	1.2577	11	0.001	1.2452
8	−1	0.0505	1.1234	3	0.0109	1.1604
9	−1	0.0901	1.0765	9	0.001	1.0988
10	10	0.0406	1.1923	7	0.1	1.1827

hyperparameters fixed at their boundaries or at the point where MAE is minimized if the squared term is significant.

The RSM process is conducted with DBN on 10 data folds. Patterns of hyperparameter effects on MAE and the search directions are summarized in Table 14. Moving along these steepest descent directions toward the optimal region gives the center points for the subsequent experiments. Then, running another CCD around these center points leads to the final regression models that yield the optimal settings for all 10 data folds. The best hyperparameter settings obtained from the final regression models and the validation MAE at these settings for DBN using RSM are provided in Table 15. The results from confirmation runs, including the average MAE, SD, half-width of 95% PI, and coverage of PI, are also shown. The PI coverages of the DBN hyperparameter settings from RSM indicate 100% reliability based on our testing.

4.5. Comparison between GS and RSM. ANOVA is performed to compare the confirmation MAE between GS and RSM (denoted as Method) for ANN, SVM, and DBN (denoted as ML) while treating data folds as blocks (see Table 16). The interaction between method and fold is mildly significant (P value = 0.094), which indicates that the average MAE of validation set between GS and RSM is statistically different in some data folds. In Table 17, further analysis using Tukey's multiple comparisons shows that the difference is significant only for the first data fold, i.e., the hyperparameters from GS give statistically better results (on average) than those of RSM. For the other nine data folds, the hyperparameter settings from GS and RSM perform statistically the same.

To investigate the reliability of using the best hyperparameters from RSM to predict unforeseen data, the three ML models with the best hyperparameters from GS and RSM are applied to predict the results in the testing dataset. Then, ANOVA is conducted to compare the average MAE of the testing set between GS and RSM (see Table 18). The ANOVA shows that there is no significant difference in the average MAE between the two hyperparameter tuning methods (i.e., GS and RSM). Therefore, this implies that the hyperparameter setting from RSM is reliable in the testing set as well.

Table 13: Analysis of variance of the second fold.

Source	Df	Adj SS	Adj MS	F-value	P value
Model	8	363.18	45.397	14.5	<0.001
HN	1	0.446	0.446	0.14	0.708
LR_{RBM}	1	0.652	0.652	0.21	0.650
LR	1	137.73	137.73	43.98	<0.001
N	1	14.968	14.968	4.78	0.034
n_i	1	153.99	153.99	49.17	<0.001
N_b	1	28.911	28.911	9.23	0.004
HN × HN	1	11.969	11.969	3.82	0.057
LR × n	1	14.51	14.51	4.63	0.037
Error	44	137.8	3.132		
Lack-of-fit	36	111.06	3.085	0.92	0.603
Pure error	8	26.738	3.342		
Total	52	500.98			

Table 14: Patterns of hyperparameter effects and search direction for DBN.

Fold	HN	LR_{RBM}	n	n_i	LR	N_b	Search direction
1	Linear (−)	Concave	Linear (−)	Linear (+)	Linear (−)	Linear (+)	Increase HN, N, LR, and fix LR_{RBM}, n_i, $N_b$at min. MAE
2	Convex	Linear (+)	Linear (−)	Linear (+)	Linear (−)	Linear (+)	Increase N, LR, and fix HN, LR_{RBM}, n_i, $N_b$at min. MAE
3	Linear (−)	Linear (−)	Linear (−)	Linear (+)	Linear (−)	Linear (+)	Increase HN, LR_{RBM}, N, LR, and fix n_i, $N_b$at min. MAE
4	Linear (−)	Linear (−)	Linear (−)	Linear (−)	Linear (−)	Linear (+)	Increase HN, LR_{RBM}, N, n_i, LR, and fix, $N_b$at min. MAE
5	Linear (+)	Linear (−)	Linear (−)	Linear (−)	Linear (−)	Linear (+)	Increase LR_{RBM}, N, n_i, LR, and fix HN, $N_b$at min. MAE
6	Linear (−)	Linear (+)	Linear (−)	Linear (−)	Linear (−)	Linear (+)	Increase HN, N, n_i, LR, and fix LR_{RBM}, $N_b$at min. MAE
8	Linear (−)	Convex	Linear (−)	Convex	Linear (−)	Concave	Increase HN, N, LR, and fix LR_{RBM}, n_i, $N_b$at min. MAE
9	Linear (−)	Linear (−)	Linear (−)	Linear (+)	Linear (−)	Linear (+)	Increase HN, LR_{RBM}, N, LR, and fix n_i, $N_b$at min. MAE
10	Linear (+)	Linear (+)	Linear (−)	Linear (+)	Linear (−)	Linear (+)	Increase N, LR, and fix HN, LR_{RBM}, n_i, $N_b$at min. MAE

Table 15: Best hyperparameter setting and the validation performance of DBN using RSM.

	Cross-validation							Confirmation runs			
Fold	HN	n_i	n	LR_{RBM}	LR	N_b	MAE	Avg MAE	SD (MAE)	95% PI half-width	PI coverage
1	7	389	10	0.0001	0.0069	1025	1.081	1.097	0.032	0.109	Yes
2	3	530	10	0.001	0.0107	1025	1.166	1.168	0.009	0.03	Yes
3	8	575	10	0.001	0.0067	350	1.073	1.083	0.011	0.036	Yes
4	3	254	10	0.001	0.0068	1025	1.083	1.096	0.013	0.042	Yes
5	3	209	10	0.001	0.0073	1700	1.087	1.093	0.009	0.031	Yes
6	**5**	**209**	**10**	**0.001**	**0.008**	**1025**	**1.000**	0.998	0.013	0.045	Yes
7	4	434	10	0.001	0.0094	1025	1.223	1.232	0.018	0.061	Yes
8	7	344	10	0.001	0.0071	1025	1.12	1.14	0.035	0.118	Yes
9	6	620	10	0.001	0.0101	1025	1.131	1.089	0.028	0.095	Yes
10	6	620	10	0.001	0.0101	350	1.299	1.203	0.064	0.215	Yes

Bold values emphasize that this is the combination of hyperparameters that results in the minimal average MAE (0.998).

Table 16: ANOVA of confirmation MAE of validation set by hyperparameter tuning methods.

Source	Df	Adj SS	Adj MS	F-value	P value
Fold	9	0.173434	0.01927	34.08	<0.001
ML	2	0.019289	0.009645	17.06	<0.001
Method	1	0.033192	0.033192	58.7	<0.001
Fold × method	9	0.009315	0.001035	1.83	0.094
Error	38	0.021486	0.000565		
Total	59	0.256716			

4.6. Discussion. Grid search (GS) is widely used in several studies as a common hyperparameter tuning method. As shown in section 4.3, implementing GS in ANN, SVM, and DBN requires many experiments, i.e., 44,100 runs, 44,880 runs, and 7,290 runs, respectively. The results in section 4.5 indicate that on average, the prediction performance of hyperparameter settings obtained from GS and RSM is statistically the same in all three ML models, while RSM requires a smaller number of runs. Specifically, with RSM, the number of runs for ANN, SVM, and DBN is 976 runs

Table 17: Tukey's multiple comparison of the confirmation MAE between GS and RSM.

	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5	Fold 6	Fold 7	Fold 8	Fold 9	Fold 10
GS	A	A	A	A	A	A	A	A	A	A
RSM	B	A	A	A	A	A	B	A	A	A

Note: Means that do not share the same letter are significantly different.

Table 18: ANOVA on MAE of testing set by hyperparameter tuning methods: GS and RSM.

Source	Df	Adj SS	Adj MS	F-value	P value
Fold	9	0.1723	0.0191	10.47	<0.001
ML	2	0.0367	0.0183	10.03	<0.001
Tuning method	1	0.0044	0.0044	2.41	0.127
Error	47	0.085969	0.001829		
Total	59	0.299374			

(97.79% saving over GS), 984 runs (97.81% saving), and 1,408 runs (80.69% saving), respectively. In other words, the benefit from using RSM has been demonstrated that it can significantly reduce the number of experiments to determine the suitable hyperparameter setting while maintaining the prediction performance.

Finally, it is worth noting that RSM, by nature, involves sequential experimentation. That is, RSM requires a modeler to run some experiments and perform data analysis to determine whether the subsequent experiment is needed. If it is the case, then findings from one experiment will guide the search in a subsequent experiment. A limitation of RSM is that this search process is not automated or has not been integrated as a hyperparameter tuning process in standard ML software.

5. Conclusion

Hyperparameter tuning is an essential process in ML algorithms. To obtain proper hyperparameter settings, GS is the common approach in many applications due to its simplicity to implement but with a drawback of many experimental runs. In this study, we propose a hyperparameter tuning process using the RSM approach. RSM is compared with GS on three ML algorithms: ANN, SVM, and DBN. A 10-fold cross-validation is performed to make sure that the ML performance is robust to the data partitioning process. The dataset used in the computational test is from an industrial user in the food industry. The purpose of the analysis is to predict the quality of the raw material in the production process. The MAE is considered a key measure. The MAE from the validation set is used to evaluate the prediction performance between the two hyperparameter tuning processes.

The comparison results indicate that the widely used GS method can give hyperparameter settings that are 80% reliable for both ANN and DBN, whereas the hyperparameter tuning process by RSM can give 90% and 100% reliability for ANN and DBN, respectively. In addition, the prediction performance from GS and RSM is directly compared using statistical analysis. The results show that the hyperparameter settings obtained from RSM can give statistically similar performance to those from GS in 9 out of 10 data folds and 7 out of 10 data folds for ANN and DBN, respectively. Although the performance from GS is slightly better than RSM, the savings in the number of runs from GS are 97.79%, 97.81%, and 80.6% for ANN, SVM, and DBN, respectively. Therefore, this demonstrates the effectiveness of using RSM as the hyperparameter tuning process for the three ML algorithms tested in this study.

We have demonstrated the robustness of the proposed method's effectiveness by testing it with three machine learning models having different characteristics: ANN with numerical hyperparameters, SVM with a mix between numerical hyperparameter and categorical (kernel function), and DBN with many numerical hyperparameters. The fundamental result is that the proposed method can be applied to ML algorithms with various characteristics for predicting a numerical response. This fundamental result also indicates the limitation of RSM that it cannot be applied to other types of responses such as binary and categorical responses found in classification problems. Directions for future research are to test the RSM tuning process in other ML algorithms and/or in other industrial applications to see whether our findings can be useful for other ML algorithms as well as other industries. [48].

Data Availability

Restrictions apply to the availability of these data. Data used in the computational study were obtained from an industrial user and are subject to a nondisclosure agreement. The data and their description may be made available from the corresponding author with the permission of the data provider.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

Acknowledgments

This research was supported by the Thailand Research Fund - Master Research Grants (no. MRG-WI515S025), Kasetsart University Research and Development Institute (no. V-T(D) 118.52), the SIIT Young Researcher Grant (no. SIIT 2019-

YRG-WP01), and the Center of Excellence in Logistics and Supply Chain System Engineering and Technology (COE LogEn), Sirindhorn International Institute of Technology (SIIT), Thammasat University.

Supplementary Materials

Table 9. Best hyperparameter setting and the validation performance of ANN using RSM. (*Supplementary Materials*)

References

[1] K. Y. Ngiam and I. W. Khor, "Big data and machine learning algorithms for health-care delivery," *The Lancet Oncology*, vol. 20, no. 5, pp. e262–e273, 2019.

[2] A. L'heureux, K. Grolinger, H. F. Elyamany, and M. A. Capretz, "Machine learning with big data: challenges and approaches," *IEEE Access*, vol. 5, pp. 7776–7797, 2017.

[3] G. D. Magoulas and A. Prentza, *Machine Learning in Medical Applications. Advanced Course on Artificial Intelligence*, Springer, New York, NY, USA, 1999.

[4] K. Kourou, T. P. Exarchos, K. P. Exarchos, M. V. Karamouzis, and D. I. Fotiadis, "Machine learning applications in cancer prognosis and prediction," *Computational and Structural Biotechnology Journal*, vol. 13, pp. 8–17, 2015.

[5] P. Probst, M. N. Wright, and A. L. Boulesteix, "Hyper-parameters and tuning strategies for random forest," *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, vol. 9, p. e1301, 2019.

[6] F. Hutter, L. Kotthoff, and J. Vanschoren, *Automated Machine Learning: Methods, Systems, Challenges*, Springer Nature, London, UK, 2019.

[7] G. A. Lujan-Moreno, P. R. Howard, O. G. Rojas, and D. C. Montgomery, "Design of experiments and response surface methodology to tune machine learning hyper-parameters, with a random forest case-study," *Expert Systems with Applications*, vol. 109, pp. 195–205, 2018.

[8] J. Bergstra and Y. Bengio, "Random search for hyper-parameter optimization," *Journal of Machine Learning Research*, vol. 13, pp. 281–305, 2012.

[9] P. Probst, A. L. Boulesteix, and B. T. Bischl, "Importance of hyperparameters of machine learning algorithms," *Journal of Machine Learning Research*, vol. 20, pp. 1–32, 2019.

[10] D. Yogatama and G. Mann, "Efficient transfer learning method for automatic hyperparameter tuning," in *Proceedings of the International Conference*, Reykjavik, Iceland, April 2014.

[11] I. Syarif, A. Prugel-Bennett, and G. Wills, "SVM parameter optimization using grid search and genetic algorithm to improve classification performance," *Telkomnika*, vol. 14, no. 4, pp. 1502–1509, 2016.

[12] A. k. Al-Fugara, M. Ahmadlou, A. R. Al-Shabeeb, S. AlAyyash, H. Al-Amoush, and R. Al-Adamat, "Spatial mapping of groundwater springs potentiality using grid search-based and genetic algorithm-based support vector regression," *Geocarto International*, vol. 8, pp. 1–20, 2020.

[13] L. Zhou, K. K. Lai, and L. Yu, "Credit scoring using support vector machines with direct search for parameters selection," *Soft Computing*, vol. 13, no. 2, pp. 149–155, 2009.

[14] A. S. Wicaksono and A. A. Supianto, "Hyper parameter optimization using genetic algorithm on machine learning methods for online news popularity prediction," *International Journal of Advanced Computer Science and Applications*, vol. 9, no. 12, pp. 263–267, 2018.

[15] L. Zhou, K. K. Lai, and J. Yen, "Bankruptcy prediction using SVM models with a new approach to combine features selection and parameter optimisation," *International Journal of Systems Science*, vol. 45, no. 3, pp. 241–253, 2014.

[16] J. H. Han, D. J. Choi, S. U. Park, and S. K. Hong, "Hyper-parameter optimization using a genetic algorithm considering verification time in a convolutional neural network," *Journal of Electrical Engineering & Technology*, vol. 15, no. 2, pp. 721–726, 2020.

[17] P. R. Lorenzo, J. Nalepa, M. Kawulok, L. S. Ramos, and J. R. Pastor, "Particle swarm optimization for hyper-parameter selection in deep neural networks," in *Proceedings of the genetic and evolutionary computation conference*, pp. 481–488, Berlin, Germany, July, 2017.

[18] J. Bergstra, R. Bardenet, Y. Bengio, and B. Kégl, "Algorithms for hyper-parameter optimization," in *Proceedings of the Twentyfourth International Conference on Neural Information Processing Systems*, vol. 24, pp. 2546–2554, Granada, Spain, December 2011.

[19] M. A. Amirabadi, M. H. Kahaei, S. A. Nezamalhosseini, and V. T. Vakili, "Deep Learning for channel estimation in FSO communication system," *Optics Communications*, vol. 459, Article ID 124989, 2020.

[20] J. Snoek, H. Larochelle, and R. P. Adams, "Practical bayesian optimization of machine learning algorithms," *Advances in Neural Information Processing Systems*, vol. 25, pp. 2951–2959, 2012.

[21] W. M. Czarnecki, S. Podlewska, and A. J. Bojarski, "Robust optimization of SVM hyperparameters in the classification of bioactive compounds," *Journal of Cheminformatics*, vol. 7, no. 1, pp. 1–15, 2015.

[22] G. N. Kouziokas, "SVM kernel based on particle swarm optimized vector and Bayesian optimized SVM in atmospheric particulate matter forecasting," *Applied Soft Computing*, vol. 93, Article ID 106410, 2020.

[23] D. C. Montgomery, *Design and Analysis of Experiments*, John Wiley & Sons, Hoboken, NJ, USA, 2017.

[24] F. Budiman, "SVM-RBF parameters testing optimization using cross validation and grid search to improve multiclass classification," *Scientific Visualization*, vol. 11, no. 1, pp. 80–90, 2019.

[25] H. Kaneko and K. Funatsu, "Fast optimization of hyper-parameters for support vector regression models with highly predictive ability," *Chemometrics and Intelligent Laboratory Systems*, vol. 142, pp. 64–69, 2015.

[26] N. Asadi and H. Zilouei, "Optimization of organosolv pre-treatment of rice straw for enhanced biohydrogen production using Enterobacter aerogenes," *Bioresource Technology*, vol. 227, pp. 335–344, 2017.

[27] L. Yu, X. Yao, S. Wang, and K. K. Lai, "Credit risk evaluation using a weighted least squares SVM classifier with design of experiment for parameter selection," *Expert Systems with Applications*, vol. 38, no. 12, pp. 15392–15399, 2011.

[28] I. H. Boyacı, "A new approach for determination of enzyme kinetic constants using response surface methodology," *Biochemical Engineering Journal*, vol. 25, pp. 55–62, 2005.

[29] A. Y. Aydar, "Utilization of response surface methodology in optimization of extraction of plant materials," *Statistical Approaches with Emphasis on Design of Experiments Applied to Chemical Processes*, Intech Open, Londan, U.K, pp. 157–169, 2018.

[30] A. Asghar, A. A. Abdul Raman, and W. M. Daud, "A comparison of central composite design and Taguchi method for

optimizing Fenton process," *TheScientificWorldJOURNAL*, vol. 2014, Article ID 869120, 14 pages, 2014.

[31] J. U. Ani, U. C. Okoro, L. E. Aneke et al., "Application of response surface methodology for optimization of dissolved solids adsorption by activated coal," *Applied Water Science*, vol. 9, no. 3, p. 60, 2019.

[32] C.-F. Mandenius and A. Brundin, "Bioprocess optimization using design-of-experiments methodology," *Biotechnology Progress*, vol. 24, no. 6, pp. 1191–1203, 2008.

[33] W. S. McCulloch and W. Pitts, "A logical calculus of the ideas immanent in nervous activity," *Bulletin of Mathematical Biophysics*, vol. 5, no. 4, pp. 115–133, 1943.

[34] D. Svozil, V. Kvasnicka, and J. Pospichal, "Introduction to multi-layer feed-forward neural networks," *Chemometrics and Intelligent Laboratory Systems*, vol. 39, no. 1, pp. 43–62, 1997.

[35] E. M. Johansson, F. U. Dowla, and D. M. Goodman, "Backpropagation learning for multilayer feed-forward neural networks using the conjugate gradient method," *International Journal of Neural Systems*, vol. 2, no. 4, pp. 291–301, 1991.

[36] C. Cortes and V. Vapnik, "Support-vector networks," *Machine Learning*, vol. 20, no. 3, pp. 273–297, 1995.

[37] S.-q. Zhang and K.-P. Lin, "Short-term traffic flow forecasting based on data-driven model," *Mathematics*, vol. 8, no. 2, p. 152, 2020.

[38] G. Battineni, N. Chintalapudi, and F. Amenta, "Machine learning in medicine: performance calculation of dementia prediction by support vector machines (SVM)," *Informatics in Medicine Unlocked*, vol. 16, Article ID 100200, 2019.

[39] N. L. da Costa, L. A. G. Llobodanin, M. D. de Lima, I. A. Castro, and R. Barbosa, "Geographical recognition of Syrah wines by combining feature selection with Extreme Learning Machine," *Measurement*, vol. 120, pp. 92–99, 2018.

[40] H. Bhavsar and M. H. Panchal, "A review on support vector machine for data classification," *International Journal of Advanced Research in Computer Engineering & Technology*, vol. 1, no. 10, 2012.

[41] C.-Y. Yeh, C.-W. Huang, and S.-J. Lee, "A multiple-kernel support vector regression approach for stock market price forecasting," *Expert Systems with Applications*, vol. 38, no. 3, pp. 2177–2186, 2011.

[42] G. E. Hinton, S. Osindero, and Y.-W. Teh, "A fast learning algorithm for deep belief nets," *Neural Computation*, vol. 18, no. 7, pp. 1527–1554, 2006.

[43] H. Li, Q. Xu, Y. He, X. Fan, and S. Li, "Modeling and predicting reservoir landslide displacement with deep belief network and EWMA control charts: a case study in Three Gorges Reservoir," *Landslides*, vol. 17, no. 3, pp. 693–707, 2020.

[44] X. Wang, T. Chen, and H. Xu, "Thickness distribution prediction for tectonically deformed coal with a deep belief network: a case study," *Energies*, vol. 13, no. 5, p. 1169, 2020.

[45] L. De Marchi and L. Mitchell, *Hands-On Neural Networks: Learn How to Build and Train Your First Neural Network Model Using Python*, Packt Publishing Ltd, Birmingham, UK, 2019.

[46] W. A. Jensen, "Confirmation runs in design of experiments," *Journal of Quality Technology*, vol. 48, no. 2, pp. 162–177, 2016.

[47] S. K. Behera, H. Meena, S. Chakraborty, and B. C. Meikap, "Application of response surface methodology (RSM) for optimization of leaching parameters for ash reduction from low-grade coal," *International Journal of Mining Science and Technology*, vol. 28, no. 4, pp. 621–629, 2018.

[48] M. S. Saad, A. M. Nor, M. E. Baharudin, M. Z. Zakaria, and A. F. Aiman, "Optimization of surface roughness in FDM 3D printer using response surface methodology, particle swarm optimization, and symbiotic organism search algorithms," *International Journal of Advanced Manufacturing Technology*, vol. 105, no. 12, pp. 5121–5137, 2019.

Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 9724623, 8 pages
https://doi.org/10.1155/2021/9724623

Research Article

Uplink Spectrum Overlay Coverage Enhancement Algorithm in 5G Network

Jian-feng Jiang[1] and Hui-jie Ding[2]

[1]*Suzhou Industrial Park Institute of Services Outsourcing, Suzhou 215123, China*
[2]*School of Artificial Intelligence, The Open University of Guangdong, Guangzhou 510091, China*

Correspondence should be addressed to Hui-jie Ding; 811054@qq.com

Received 13 September 2021; Accepted 22 October 2021; Published 22 December 2021

Academic Editor: Kim-Hua Tan

The imbalance between the uplink and downlink rates and coverage of the 5G network has led to limited vertical industry services. Aiming at breaking the imbalance between the uplink and downlink rates and improving the coverage of 5G network, a uplink coverage enhancement algorithm is designed from the aspects of networking mode, bandwidth, uplink and downlink subframe ratio, etc. It uses high- and low-frequency time-frequency joint scheduling to enable uplink full-time slot scheduling, thereby improving uplink coverage and rate. According to the actual test on the live network, the results show that the super-uplink algorithm can increase the near-point uplink rate by 15% to 30%, increase the uplink rate for indoor midpoint scenarios by 40% to 80%, and increase the uplink rate for outdoor and indoor weak spot scenarios by 100% to 400%.

1. Introduction

When redefining 5G networks guided by industry needs, the 2C market has mainly high speed and the current 5G network speed can easily reach more than 1 Gpbs downstream, which is fast enough to meet the market demand. However, in the 2B market, vertical industries have put forward new requirements for upstream speeds and latency has become the most important requirement. For example, the demand for uplink speed of the smart mining factory has reached more than 100 Mbps, and the end-to-end delay requirement is less than 15 ms. The 5 G uplink rate is limited by multiple factors such as terminals, networks, and frequency spectrum, which make it difficult to meet the uplink rate requirements of vertical industries. The transmitting power of the terminal is much smaller than the transmitting power of the base station, and the difference between the two powers is nearly a thousand times. In the mainstream time slot ratio of 7 : 3, 4 : 1, or 8 : 2, the uplink proportion is very small. At present, the C-band propagation loss in the mainstream 5G frequency band is huge and the penetration loss of 3.5 GHz in a typical wall is as high as 26 dB.

As the 5G network is still mainly for mass services at this stage, the time slot ratio is still dominated by downlink time slots [1, 2]. The difference in uplink and downlink coverage is huge, and the uplink coverage is obviously limited [3–5]. In the deployment of vertical industry applications, its uplink coverage and speed are a major requirement. How to solve the combination of 5G high- and low-frequency spectrum is a hot issue of current research. Commercial use of 5G networks only started at the end of 2019. In the early stage of 5G network operation, the literature [4] proposed using 4G and 5G co-site strategies to increase the uplink rate. However, due to the high frequency band and low time slot of the network, the uplink coverage of the 5G network is not continuous [6]. The study in [7] proposes to use spectrum aggregation technology to solve the uplink and downlink access of 5G heterogeneous networks, but it cannot completely solve the problem of cell handover [8, 9]. The study in [10] uses link adaptation algorithms to control the uplink channel power, which can optimize the uplink to a certain extent, but it cannot solve the essential problem. In view of the above problems, the algorithm in this paper realizes the complementarity of

FDD uplink time slot and TDD uplink time domain and improves uplink coverage and throughput.

In terms of the 3.5 GHz high-frequency site, China Telecom also has 1.8/2.1 GHz low-frequency sites. The number of sites nationwide is about 60,000, and the load is low. Therefore, incorporating the 1.8/2.1 GHz frequency band into 5G network construction can obtain greater uplink and downlink advantages.

2. Analysis of 5G Network Uplink and Downlink Coverage

2.1. 5G Spectrum. Spectrum is the core resource in the field of mobile communications [11, 12]. The 5 G NR (new radio) spectrum defined by the 3GPP standard mainly includes sub-6 GHz (410–7 125 MHz) and millimeter wave (24 250–52 600 MHz). It has multiple modes such as frequency division duplex (FDD), time division duplex (TDD), and supplementary uplink (SUL). At present, commercial 5G networks mainly use the TDD mode 3.5 GHz and 2.6 GHz frequency bands. Compared with the 1.8 GHz and 2.1 GHz frequency bands used by 4G FDD networks, they have a large bandwidth advantage. Its single-user peak rate is significantly higher than of 4G under the condition of low path loss, but the penetration loss is higher. The uplink and downlink time slot ratios of commercial 5G networks are 3 : 7, 1 : 4, or 2 : 8, and the available uplink time slots are relatively small. Table 1 is the spectrum information status of today's operators.

2.2. Uplink and Downlink Rate. The application of 5G network's large bandwidth and large-scale array antenna gain has greatly improved the rate of 5G network compared with that of 4G networks. Under ideal conditions, the downlink rate of 5G networks is as high as 1.2 Gbps, which is about 10 times the rate of 4G networks. The uplink rate is as high as 130 Mbps, which is about 4 times the rate of the 4G network. However, in a nonideal state, when the 5G network RSRP is at the coverage edge of −110 dBm to −120 dBm, the downlink rate can be maintained at 100 to 300 Mbps and the minimum uplink rate is only about 2.58 Mbps. The uplink and downlink rates are shown in Figure 1.

3. Uplink Coverage Enhancement Algorithm

3.1. Principles of Coverage Enhancement Algorithm. The uplink coverage enhancement algorithm uses NR FDD to enhance uplink coverage, experience, and capacity. The FDD frequency band is low, the coverage is strong, and the frequency division duplex transmission has no additional waiting delay, but the transmission bandwidth is small. The TDD frequency band has a large bandwidth, and the uplink and the downlink both use mature applications of MIMO technology. Under the premise of the same subcarrier spacing, the coverage and delay are weaker than FDD. Coverage enhancement algorithm technology realizes the uplink transmission of FDD NR and TDD NR, as the principle shown in Figure 2.

Taking the influence of signal coverage in high-frequency band and low-frequency band into account, there are two situations in the time slot scheduling—the mid-near-point area and the far-point area. In the mid-near-point area, the algorithm mainly improves the uplink capacity and user experience. In the far-point area, the algorithm mainly improves the C-band 3.5 GHz coverage. In this way, the Sub-3 GHz spectrum is fully utilized to realize 5G full-time slot scheduling.

3.2. Design of Uplink Coverage Enhancement Algorithm

3.2.1. The First Step: User (UE) Access. The UE is in idle mode when it is powered on and accesses the user equipment in the 3.5 GHz frequency band. Currently, most 5G mobile phone chips support 5G networks, and the UE can dynamically change the configuration. When the UE is at the edge of the 5G network, the network uplink coverage is limited and the 5G network controls the UE to access the PUSCH of the Sub-3G network for data transmission. The basis for judging whether the 5G uplink coverage is limited is the 5G uplink SINR. When the SINR is greater than the threshold, it indicates that the uplink coverage is good and the C-band network is selected. When the SINR is less than the threshold, the Sub-3G network is selected. The process is shown in Figure 3.

3.2.2. The Second Step: Allocation of Uplink Frequency-Domain Resource. The PUSCH is configured with two frequency bands, C-band and Sub-3G, and the PUCCH is configured with only C-band. The process is shown in Figure 4. According to the latest 5G R16 standard, DCI formats indicate whether the DCI information is uplink or downlink scheduling information. It occupies 1 bit, a value of 0 indicates uplink, and a value of 1 indicates downlink. The uplink DCI mainly indicates uplink PUSCH transmission, including two types of field information of DCI format 0_0 and DCI format 0_1.

When the field information is DCI format 0_0, if DCI format 0_0 is scrambled by C-RNTI or CS-RNTI or MCS-C-RNTI, the number of bits occupied by frequency domain resources is calculated by the following formula:

$$\left\lceil \log_2\left(N_{RB}^{UL,BWP} \frac{N_{RB}^{UL,BWP}+1}{2} \right) \right\rceil, \tag{1}$$

$$\left\lceil \log_2\left(N_{RB}^{UL,BWP} \frac{N_{RB}^{UL,BWP}+1}{2} \right) \right\rceil - N_{UL\_HOP}. \tag{2}$$

When PUSCH frequency hopping is used, $N_{RB}^{UL,BWP}$ is the size of the activated UL BWP. For the uplink resource allocation type is 1, the PDSCH is used for frequency hopping situation, N_{UL_HOP} is the number of bits which is used to indicate frequency offset. If the frequency hopping offset list contains 2 offset values, N_{UL_HOP} is set to 1. If the frequency hopping offset list contains 4 offset values, N_{UL_HOP} is set to 2. At this time, formula (2) is used to calculate the number of remaining bits to indicate frequency-domain resource

Table 1: Comparative analysis of operators' existing spectrum resources.

	China Mobile (MHz)	China Telecom	China Unicom (MHz)
4.9 (GHz)	100		
3.5		100 MHz	100
2.6	160		
2.1		2 × (20 + 10) MHz	

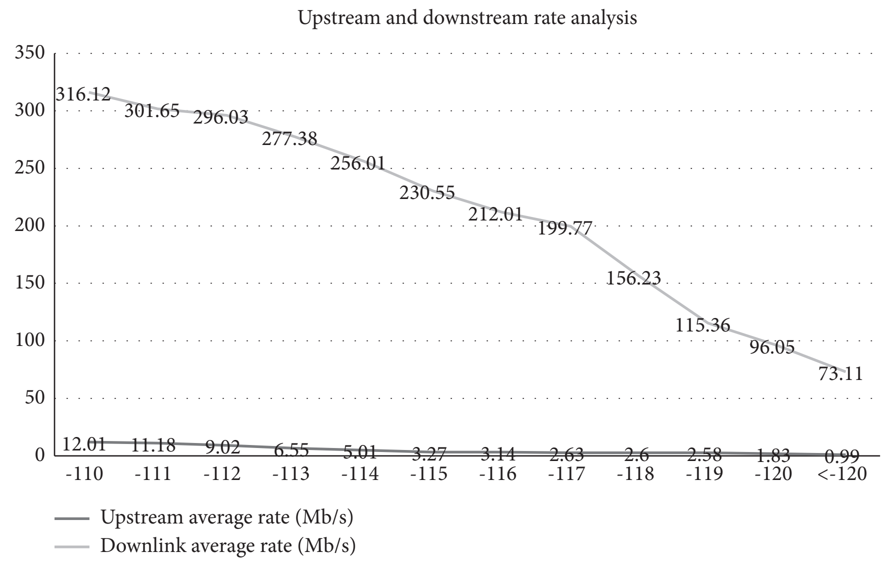


Figure 1: Comparison of the average uplink and downlink rate at the edge of network coverage.

allocation. Since the uplink resource allocation type is 1 and the PDSCH frequency hopping is not used, the number of bits calculated by the formula (1) indicates the frequency-domain resource allocation.

When DCI format 0_0 is scrambled by TC-RNTI, $N_{\mathrm{RB}}^{\mathrm{UL,BWP}}$ in formula (1) is the size of the initial UL BWP. If its value is less than 50, then $N_{\mathrm{UL\_HOP}}$ is set to 1; otherwise, N_{UL_HOP} is set to 2.

When the local segment information is DCI format 0_1, the cross-domain carrier scheduling feature is enabled and the carrier indicator field is generated.

When the field information is 0 bits, it indicates the current cell, and when the field information is 3 bits, it indicates the corresponding cell. The frequency-domain resource allocation field N_{RBG} indicates the total number of UL BWP RBGs, and the calculation formula is shown in

$$N_{\mathrm{RBG}} = \left\lceil \frac{\left(N_{\mathrm{BWP},i}^{\mathrm{size}} + \left(N_{\mathrm{BWP},i}^{\mathrm{start}} \bmod P\right)\right)}{P} \right\rceil. \tag{3}$$

In formula (3), P represents all other RBG sizes, and the first RBG size is calculated by the following formula:

$$\mathrm{RBG}_0^{\mathrm{size}} = P - N_{\mathrm{BWP},i}^{\mathrm{start}} \bmod P. \tag{4}$$

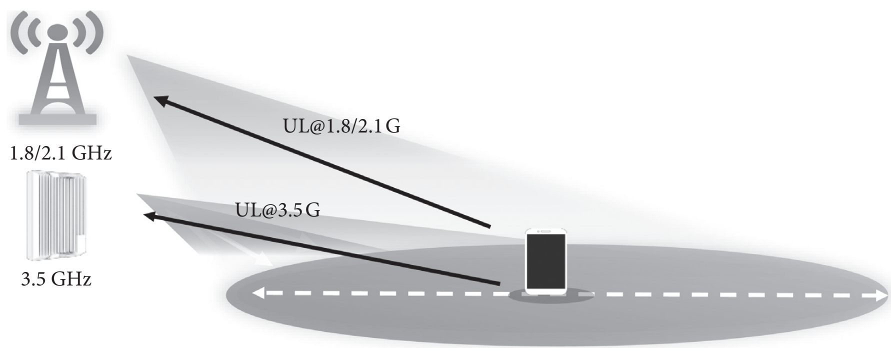
If $(N_{\mathrm{BWP},i}^{\mathrm{start}} + N_{\mathrm{BWP},i}^{\mathrm{size}}) \bmod P$ is greater than 0, the last RBG size calculation formula is as follows:

$$\mathrm{RBG}_{\mathrm{last}}^{\mathrm{size}} = \begin{cases} \left(N_{\mathrm{BWP},i}^{\mathrm{start}} + N_{\mathrm{BWP},i}^{\mathrm{size}}\right) \bmod P, & \left(N_{\mathrm{BWP},i}^{\mathrm{start}} + N_{\mathrm{BWP},i}^{\mathrm{size}}\right) \bmod P > 0, \\ P, & \text{otherwise.} \end{cases} \tag{5}$$

If uplink resource allocation type 1 is configured, the value of this field is calculated by formula (1). The $N_{\mathrm{RB}}^{\mathrm{UL,BWP}}$ is the size of the activated UL BWP. If both of uplink resource allocation type 0 and type 1 are configured, the value of this field is calculated by

$$\max\left(\left\lceil \log_2\left(\frac{N_{\mathrm{RB}}^{\mathrm{UL,BWP}}\left(N_{\mathrm{RB}}^{\mathrm{UL,BWP}} + 1\right)}{2}\right), N_{\mathrm{RBG}} \right\rceil\right) + 1. \tag{6}$$

The uplink resource allocation type is 0, and the value of N_{RBG} indicates frequency-domain resource allocation. The uplink resource allocation type is 1, and the value calculated by formula (1) indicates frequency-domain resource allocation. When it uses PDSCH for frequency hopping, the frequency hopping offset list contains 2 offset values and N_(UL_HOP) is set to 1. If the frequency hopping offset list contains 4 offset values, N_(UL_HOP) is set to 2. At this time, formula (2) is used to calculate the number of remaining bits to indicate



Use Sub3 G to enable full time slot transmission of uplink data, including the downlink time of TDD

C-Band	D	D	D	S	U	D	D	S	U	U
Sub-3 G	U		U		X	U	U		X	

S Special time slot
D Downlink transmission
U Uplink transmission

Figure 2: Principle of uplink coverage enhancement.

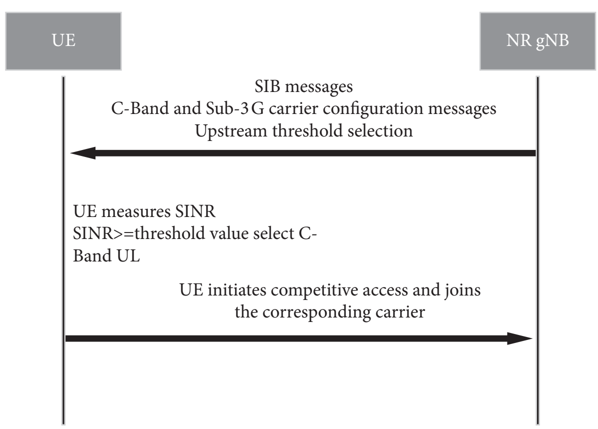


Figure 3: User access.

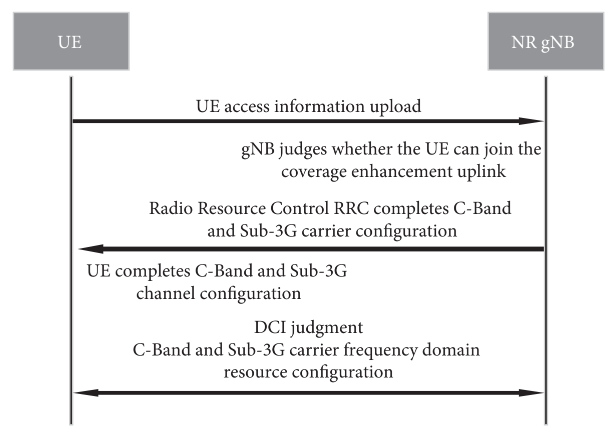


Figure 4: Channel configuration.

frequency-domain resource allocation. The uplink resource allocation type is 1, the PDSCH frequency hopping situation is not used, and the value calculated by formula (1) is used to indicate frequency-domain resource allocation.

3.2.3. The Third Step: Cell Handover. When the UE is moving, the coverage enhancement NR spectrum and the cell handover process are as shown in Figure 5.

3.2.4. The Fourth Step: Uplink Time-Domain Resource Scheduling. The base station performs uplink data time slot scheduling, which is determined by the time-domain resource assignment field in DCI format 1_0 and DCI format 1_1. The value m of the field time-domain resource assignment is used to determine the row index $m+1$ in the time-domain resource assignment table. The allocation position of the PUSCH time slot is calculated by

$$\left\lfloor n * \frac{2^{u}\text{PUSCH}}{2^{u}\text{PDCCH}} \right\rfloor + k_0. \quad (7)$$

Here, n is the time slot for scheduling DCI, k_0 is the time slot offset based on PDCCH receiving PUSCH, and 2^uPUSCH and 2^uPDCCH are configured subcarrier intervals. The start and length indicator SLIV determines the number of start symbols S and consecutive symbols L in the PUSCH time domain.

$$\text{SLIV} = \begin{cases} 14 * (L-1) + S, & L-1 \le 7, \\ 14 * (14 - L + 1) + (14 - 1 - S), & \text{otherwise.} \end{cases} \quad (8)$$

Here, $0 < L \le 14$-S. The base station performs time-domain scheduling through DCI, and the scheduling algorithm in the mid-near-point area and the far-point area are shown in Figure 6.

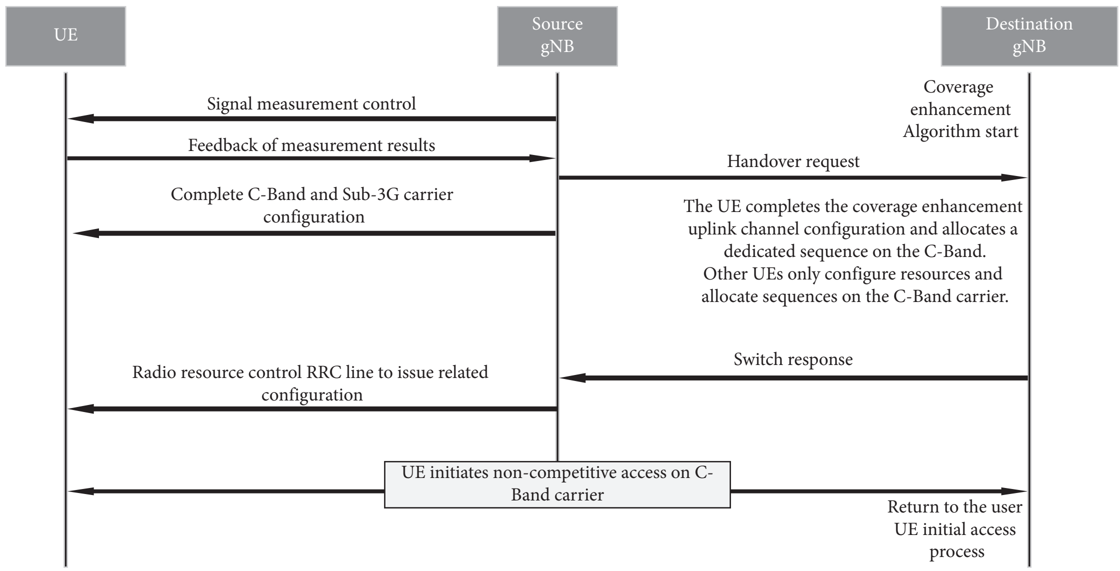


Figure 5: Cell handover process.

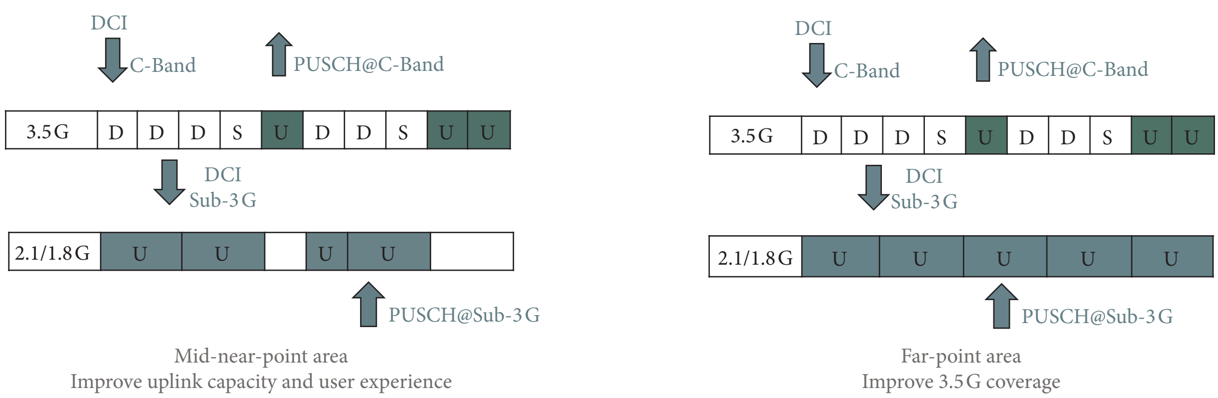


Figure 6: Two types of regional time-domain scheduling.

4. Network Emulation

4.1. Uplink Equivalent Bandwidth Comparison. In the actual network environment, the uplink performance comparison of different locations is tested by selecting the network spectrum of different operators and setting the equivalent bandwidth. The test environment is shown in Table 2.

The test result is shown in Figure 7. The uplink coverage enhancement algorithm in the 3.5 G + 2.1 G network has a near-point area uplink resource utilization rate of 100%, which improves the uplink capacity and experience by 30%. In far-point areas, the uplink coverage enhancement algorithm uses 2.1 G uplink resources to increase the 3.5 G coverage rate by 100%.

4.2. Fixed-Point Test. The test scenario is selected as a mining area in the industrial Internet field of the vertical industry. The main coverage direction of the opened sectors is the mining area, which is a basin topography, and the lowest platform is flat. Fixed-point test scenario Area 1 is about 325 meters away from the station horizontally, Area 2 is about 505 meters away from the station horizontally, and Area 3 is about 630 meters away from the station horizontally. The station and terminal configuration parameters are shown in Table 3.

The test data are shown in Table 4.

The test results are shown in Figure 8. The uplink coverage enhancement algorithm uses high- and low-frequency time-frequency joint scheduling and 3.5 G + 2.1 G uplink full-slot scheduling, and the rate is improved. The use of 2.1 G frequency band to spread data in weak coverage areas can reduce loss and enhance TDD uplink coverage.

From the statistics, we can see that in the near-point peak scenario, after the uplink coverage enhancement algorithm is executed, the uplink rate is increased by about 20%. In the outdoor midpoint scenario, after the uplink coverage enhancement algorithm is executed, the uplink rate is increased by 40% to 80%. In outdoor weak coverage scenarios, after the uplink coverage enhancement algorithm is executed, the uplink rate is increased by 100% to 400%.

Table 2: Horizontal comparison parameters.

Uplink algorithm	Spectrum bandwidth
China Mobile	2.6 G(20M)@2T
China Telecom	3.5 G(30M)@2T
China Telecom uplink coverage enhancement	3.5 G(30M)@2T&2.1 G(14M)@1T

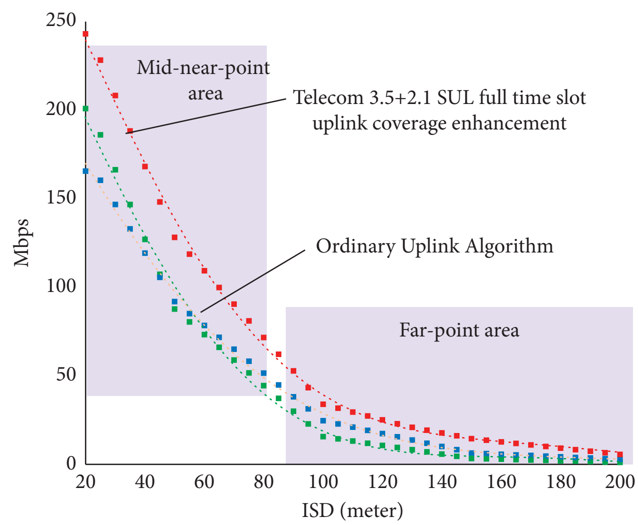


Figure 7: Horizontal performance comparison.

Table 3: Uplink coverage enhancement algorithm test site and terminal parameter configuration.

Parameter	NR TDD 3.5 G	Uplink coverage enhancement 3.5 G + 2.1 G
Uplink bandwidth	100 MHz	3.5 G 100 MHz + 2.1 G 20 MHz
Uplink and downlink time slot ratio	7 : 3	NA
Base station antenna	64R	4R
Base station power	200 W	200 W
Terminal type	CPE PRO	
Terminal antenna	2T4R	3.5 G 2T + 2.1 G 1T
Frequency range	3400~3500 MHz	1920~1940 MHz

Table 4: Test data of the mining area.

Test area	Test location	SSB-RSRP (dBm)	NR 3.5 G TDD uplink rate (Mbps)	Coverage-enhanced uplink rate (Mbps)	Uplink gain (%)
Area 1	P1	−75.77	234.93	273.37	16.36
	P2	−76.29	233.30	273.19	17.10
	P3	−79.10	237.07	277.19	16.92
	P4	−80.12	236.94	277.16	16.97
Area 2	P5	−86.96	91.43	131.29	43.59
	P6	−87.52	55.90	93.28	66.87
	P7	−87.59	82.21	122.16	48.59
	P8	−89.85	48.10	83.59	73.80
	P9	−91.82	37.35	65.67	75.83
	P10	−102.28	10.93	29.43	169.41
Area 3	P11	−102.97	10.69	28.33	165.08
	P12	−110.52	1.78	7.31	310.27
	P13	−110.77	1.74	7.64	339.57
	P14	−112.03	1.03	7.90	668.75
	P15	−112.98	1.10	5.52	403.73

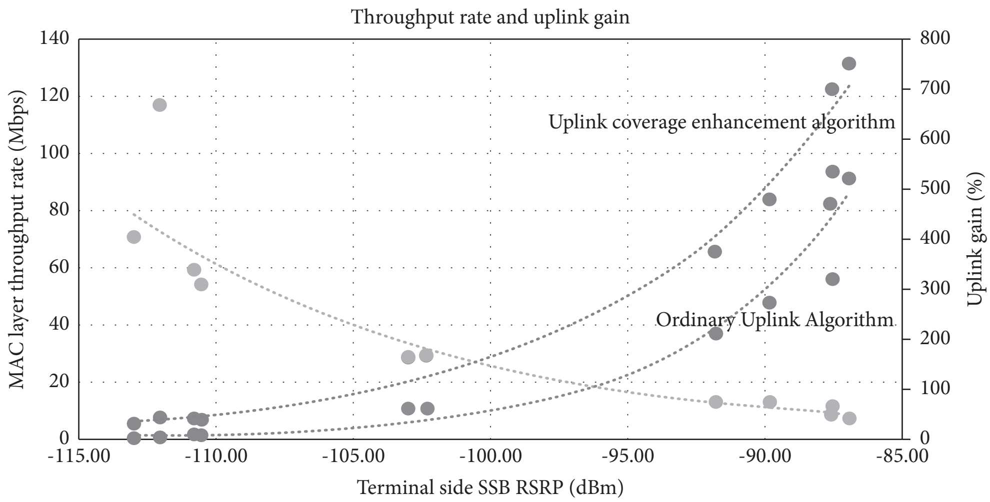


Figure 8: Throughput and gain analysis.

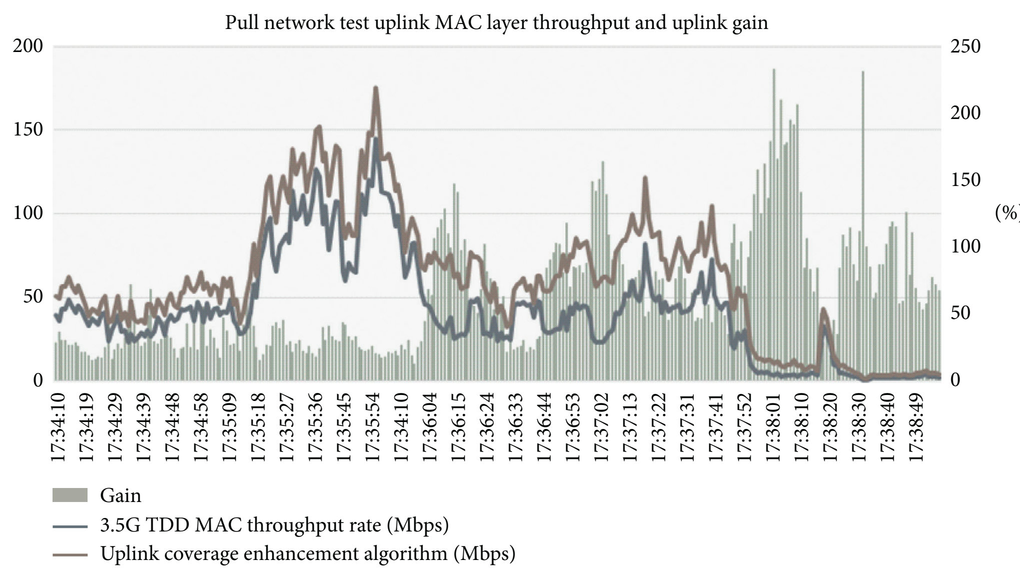


Figure 9: MAC layer throughput rate and super-uplink gain analysis.

4.3. Pull Net Test. By testing the highest and lowest platform routes, the test results of the uplink coverage enhancement algorithm are as shown in Figure 9. It can be seen that after the uplink coverage enhancement algorithm is executed, the average uplink rate increase ratio reaches 20% to 40%.

5. Conclusion

This paper designs a 5G network-based uplink coverage enhancement algorithm. Through the superposition of C-band spectrum and Sub-3G uplink spectrum, it greatly increases the uplink spectrum resources and improves the user capacity and experience of the 5G network. Tests have proved that the algorithm can solve the 5G uplink and downlink coverage problems and increase the rate of edge users, which is evolutionary. With the gradual recultivation of existing frequency bands, the available frequency bands for 5G will be more abundant and multiband carrier aggregation and collaborative networking will be more widely used, providing a better user experience.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

This work was funded by the QingLan Project of Jiangsu Province (202010).

References

[1] B. Mengesha, P. T. Ferrera, and R. Gaudino, "Analysis of 5G new radio uplink signals on an analogue-RoF system based on DSP-assisted channel aggregation," *Applied Sciences*, vol. 9, no. 1, 2018.

[2] B. Lahad, M. Ibrahim, S. Lahoud, K. Khawam, and S. Martin, "Joint modeling of TDD and decoupled uplink/downlink access in 5G HetNets with multiple small cells deployment," *IEEE Transactions on Mobile Computing*, vol. 20, 2020.

[3] H. Uzawa, K. Honda, H. Nakamura et al., "Dynamic bandwidth allocation scheme for network-slicing-based TDM-PON toward the beyond-5G era," *Journal of Optical Communications and Networking*, vol. 12, no. 2, pp. A135–A143, 2019.

[4] N. Zhang, J. Wang, G. Kang, and Y. Liu, "Uplink non-orthogonal multiple access in 5G systems," *IEEE Communications Letters*, vol. 20, no. 3, pp. 458–461, 2016.

[5] R. P. Verdecia and J. I. Alonso, "Performance analysis of two-hop mmWave relay nodes over the 5G NR uplink signal," *Applied Sciences*, vol. 11, no. 13, p. 5828, 2021.

[6] H. Shen, Q. Ye, W. Zhuang, W. Shi, G. Bai, and G. Yang, "Drone-small-cell-assisted resource slicing for 5G uplink radio access networks," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 7, 2021.

[7] M. A. Lema, E. Pardo, O. Galinina, S. Andreev, and M. Dohler, "Flexible dual-connectivity spectrum aggregation for decoupled uplink and downlink access in 5G heterogeneous systems," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 11, pp. 2851–2865, 2016.

[8] X. Li, Z. Zhong, Y. Niu, and H. Zhou, "Backoff HARQ for Contention-Based Transmission in 5G Uplink," in *Proceedings of the 4th EAI International Conference, IoTaaS 2018*, Xian, China, vol. 7, pp. 284–291, November 2019.

[9] W. Tang, S. Kang, B. Ren, X. Yue, and X. Zhang, "Uplink pattern division multiple access in 5G systems," *IET Communications*, vol. 12, no. 9, pp. 1029–1034, 2018.

[10] S. Sun, S. Moon, and J. K. Fwu, "Practical link adaptation algorithm with power density offsets for 5G uplink channels," *IEEE Wireless Communication Letters*, vol. 9, 2020.

[11] B. K. Letaief, P. Fan, Z. Chen, and Y. Dong, "Mobility-Aware Uplink Interference Model for 5G Heterogeneous Networks," *IEEE transactions on wireless communications*, vol. 15, 2016.

[12] G. Celik and H. Celebi, "TOA Positioning for Uplink Cooperative NOMA in 5G networks," *Physical Communication*, vol. 36, 2019.

Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 4920167, 11 pages
https://doi.org/10.1155/2021/4920167

Research Article

Effects of Output Quality and Result Demonstrability on the Perceived Usefulness of GPS Sports Watches from the Perspective of Industry 4.0

Ming-Zhu Yuan,[1] Jan-Wei Lin,[2] Cheng-Chia Yang,[1] I-Chi Wang,[3] and Chin-Hsien Hsu [4]

[1]*Department of Healthcare Administration, Asia University, Taichung, Taiwan*
[2]*Center for General Education Sports Administrative Organization, National Chi Nan University, Nantou County, Taiwan*
[3]*Department of Industrial Education and Technology, National Changhua University of Education, Changhua City, Taiwan*
[4]*Department of Leisure Industry Management, National Chin-Yi University of Technology, Taichung City, Taiwan*

Correspondence should be addressed to Chin-Hsien Hsu; hsu6292000@yahoo.com.tw

Received 24 August 2021; Revised 22 October 2021; Accepted 5 November 2021; Published 20 November 2021

Academic Editor: Kuei-Hu Chang

In the wave of Industry 4.0, GPS sports watches are redeveloping towards digitization and intelligence. Whether the information is correct and real-time, operation interfaces easy to use and the displayed information easy to understand have become issues that consumers and manufacturers emphasize. Thus, this study investigated the effects of output quality and result demonstrability on the perceived usefulness of GPS sports watches with participants of the 2020 Taiwan International Triathlons as the research subjects. In total, 280 respondents, who participated in the 2020 Taiwan International Triathlon, were selected by purposive sampling for a questionnaire survey. The statistical software SPSS was employed to file the data, and the statistical software of AMOS was adopted to analyze the correlation among variables. According to the results, (1) output quality has significantly positive effects on perceived usefulness; (2) result demonstrability has significantly positive effects on perceived usefulness; (3) perceived ease of use has significantly positive effects on perceived usefulness; (4) perceived ease of use has significantly positive effects on behavioral intention to use; and (5) perceived usefulness has significantly positive effects on behavioral intention to use.

1. Introduction

With technological development and innovation, new business models and production modes have been emerging in global industries. The global manufacturing industry has moved towards service and intelligence, giving rise to the concept of Industry 4.0. According to [1], under the high-tech strategy issued by the German government in 2011, Industry 4.0 (I4.0), or the Fourth Industrial Revolution, is jointly funded by the Federal Ministry of Education and Research and the Federal Ministry of Economy and Technology to promote the computerization, digitalization, and intelligence of the manufacturing industry. The goal of Industry 4.0 is not to create new industrial technologies. Instead, it integrates the technical information and business activity information related to the whole life cycle of the manufacturing industry to establish smart factories with high adaptability, high production elasticity, and high resource efficiency. Taiwan saw the global trend of smart manufacturing and proposed a "Productivity 4.0 Initiative" in 2015 to push the country's industry to the next stage. Wang and Ma [2] pointed out that the "Productivity 4.0 Initiative" promoted by Taiwan's Executive Yuan covers the agriculture and service industries in addition to the manufacturing industry. The main strategy involves making industries enter the stage of 4.0 by combining advantages of intelligent machinery and information communication in Taiwan and using technologies, such as the Internet of Things (IoT), intelligent robots, big data, and lean management. As mentioned above, Industry 4.0 not only focuses on creating new industrial technologies, but also emphasizes directly connecting with end-users or consumers by multiple intelligent methods. According to Ho [3], the primary difference of Industry 4.0 lies in the cyber-physical systems that integrate computing, communication, and control to connect various equipment systems in production by means of computers, sensors, and new-generation network techniques and achieve intelligent instant messaging and services with the ability of real-time perception and control through communication and interaction among them. The interaction between intelligent production and IoT will bring completely new changes to economic, political, and social environments.

Wearable sports devices are also being developed in such environments. Lin [4] emphasized that, with the advent of Industry 4.0, the concept of "quantified self" gradually seeps into people's daily lives, and they begin to record their body information through technology to pursue sports performance or stay healthy. Noteworthily, wearable devices are one of the key development projects of this trend. The survey and research data of Garnet [5] proved this view, showing that the global gross expenditure on wearable devices is forecasted to be US$81.5 billion in 2021, or 18.1% more than that in 2020. The COVID-19 pandemic is an important factor driving such market growth. In other words, mobile communication devices are mainstream today. Furthermore, according to Statist's prediction, global wrist wearable devices will increase from 70 million in 2019 to 110 million in 2023 [6].

According to the statistical data of Sports Administration, Ministry of Education, R.O.C. [7], in the 2019 sports status survey, nearly 80% of sports people most commonly do outdoor recreational sports, and 33.6% of the national population regularly participates in sports, hitting a record high with 20,000 people more than that in 2018. In other words, people have more opportunities to go outside for exercises, such as jogging, hiking, mountaineering, and canoeing. In terms of regular sports, the government and private agencies provide more spaces for people to do various indoor sports, which increase the opportunities to use GPS sports watches. The Sports Administration [7] echoed this development trend and pointed out that as Taiwan is experiencing a fitness craze, a new type of smart fitness that combines sports and technology has become a development trend. At the same time, various bureaucratic ministries are investing relevant resources. For instance, the Technology Department of the Ministry of Economic Affairs and the Institute for Information Industry set up the Sports Technology Alliance to serve enterprises, universities, and research institutes and promote the transformation and development of the sports industry.

People active in sports often use wearable devices, such as smart bracelets or watches, to understand their heartbeat, blood pressure, and other physiological information to provide a reference for personal trainers or themselves to develop sports regimens. Although GPS sports watches have become more mature today, people still face concerns about inaccurate and incomplete recorded data. For example, according to Shcherbina et al. [8], when heart rates and calorie expenditure are recorded by wrist wearable devices, the data of cycling are more accurate than that of walking; that is, the results do not have the same accuracy for different intensity and sports patterns. According to the results, when people record information by GPS sports watches, the accuracy and completeness of the recorded information are key indicators of product acceptance, indicating that GPS sports watch users focus on "output quality." In other words, "output quality" helps users understand the practicability of GPS sports watches and allows them to deliver results to others more clearly. For instance, the accurate tracking and physiological information recorded by GPS sports watches provides a reference for people to participate in the same activities, which corresponds to the meaning of GPS sports watches in exhibiting "result demonstrability."

According to the extended technology acceptance model proposed by Venkatesh and Davis [9],"output quality" and "result demonstrability" have effects of unperceived usefulness. People use GPS sports watches hoping that the data provided by such watches can record their own experience in sports and even improve the efficiency of self-training. Therefore, users naturally care about the accuracy of information recorded by GPS sports watches and the effects of GPS sports watches, both of which the extended technology acceptance model focuses on. The extended technology acceptance model can help understand people's behavior of adopting new technologies.

After a comprehensive review of the literature [10–12], it is found that most studies focus on the consumption behavior models of GPS sports watch consumers on wearable sports devices and how these devices improve consumers' sports performance rather than explore their behavior and experience of the new technology in wearable sports devices. Hence, this study intends to explore the experience of GPS sports watch consumers in using GPS sports watches to record their exercise process during sports. The extended TAM proposed by Venkatesh and Davis [9] shows the effects of "output quality" and "result demonstrability" on "perceived usefulness." It also helps understand people's behavior of adopting the new technology of wearable sports devices. Therefore, this study treated the participants of the Taitung International Triathlon as the research subjects and explored the effects of output quality and result demonstrability of GPS sports watches on the perceived usefulness from the perspective of Industry 4.0 by the extended TAM. Based on the results, suggestions are proposed for reference.

According to the literature review, while most studies on wearable sports devices focus on consumer behaviors [10, 13–15], some focus on sports performance [11, 12, 16–19]. However, there are only few studies on user experience. Therefore, this paper, with participants of a Taiwan international triathlon as the research subjects, explores the effects of output quality and result demonstrability of GPS sports watches on perceived usefulness from the perspective of Industry 4.0 via the extended technology acceptance model and makes suggestions at the end of the paper for reference.

2. Literature Review

2.1. The Theory of Technology Acceptance Model. In early 1988, Davenport and Prusak [20] proposed that the evolution process of knowledge includes data, information, knowledge, and wisdom, where knowledge is collected and applied to take actions in the intelligent stage. This process indicates that while "data" show facts of the past, today's "wisdom" stage focuses on the ideas and decisions proposed in the future. With the intelligence of information technology and network techniques, the concept of Industry 4.0 helps enterprises develop systems that can predict human behaviors and habits and develop abilities to detect changes and make real-time decisions. According to Lee [21], Industry 4.0 was first proposed in Hannover Messed in 2011. In 2012, Germany's federal government, in a joint effort with German industries and research institutions, formed a workgroup of Industry 4.0, aiming to implement one of the ten plans of High-tech Strategy 2020 through this project. In recent years, countries have been fully aware of the advantages of Industry 4.0 and devoted their efforts to topics and technologies related to Industry 4.0. Hsiung [22] pointed out that improving national industrial competitiveness through the implementation of Industry 4.0 or smart manufacturing systems has become the core of many important national industrial policies in recent years. Hsu [23] agreed with this view and considered that smart manufacturing upgrading is the common goal of Industry 4.0 development in countries around the world. Bureaucratic units of the Taiwan government have paid attention to Industry 4.0 development in various countries. According to the Executive Yuan [24], in the past three years, the world's major countries have actively promoted the construction of cyber-physical intelligent manufacturing, production, and sales systems for rapid response or market demand prediction, such as Germany's "Industry 4.0," the United States' reindustrialization policy, Japan's man-machine coexistence future factory, South Korea's next-generation smart factory, or China's "Made in China 2025" plan. In 2016, the Taiwan government formulated the "Productivity 4.0 Initiative" to develop technologies, such as intelligent machines, IT, big data, and cloud computing, and improve the added values of products and services in manufacturing, commerce, services, and agriculture [23].

Wang and Chiang [1] considered that the Industry 4.0 technology concept includes cyber-physical systems (CPS), Internet of things (IoT), and Internet of service (IoS) and linked the design and development data, equipment, personnel, manufacturing process, and digital data in the production process. Equipment can perform independent monitoring, analysis, and judgment and conduct autonomous communication cooperation according to the production status to make the production process more flexible. Therefore, wearable devices continuously collect users' physiological information using the computing power of IoT by combining artificial intelligence technology with sensor applications to build effective databases and then providing users with more suggestions on sports through applications and comparative analysis.

With such technological progress, people have more opportunities to gain access to technological products than ever before. For various technological products, understanding consumers' behaviors and usage habits has become the focus of industries. Lee et al. [25] pointed out that, in theories of information technology equipment acceptance, the technology acceptance model (TAM), proposed by Davis in 1986, is the most widely used and can be applied to research with different people, information systems, and working places at different times. TAM was gradually developed from the theory of reasoned action (TRA). Proposed by Ajzen and Fishbein [26], TRA has been widely used in the last few decades in exploring and verifying individual behaviors. They argue that individuals' behavior, beliefs, and evaluations directly affect individual attitudes to certain behaviors. Further, attitudes and subjective norms will affect individual behavioral intentions, which are determinants directly affecting individual behaviors. Therefore, many factors affect individual acceptance of information technology, including attitudes, subjective norms, and perceived behavioral control. Through the technology acceptance model developed from the theory of reasoned action, Davis [27] concluded that perceived usefulness and perceived ease of use of information technology are two main determinants affecting behavioral intentions. Perceived usefulness means that users subjectively consider this technology to be helpful for job performance and the future. Meanwhile, perceived ease of use refers to the degree to which users perceive that the technology is easy to use. The easier the technology is to use, the more confident the users are in self-efficacy and self-control, and the more positive their attitudes are towards systems. In this study, if people use GPS sports watches and find that the recorded data and provided information can help them improve their sports efficiency or training performance, their acceptance of GPS sports watches may be high. On the other hand, if the GPS sports watches provide users with intuitive and easy-to-use feelings in operation interface and data transmission, people may be more highly willing to use GPS sports watches.

2.2. The Theory of Extension of the Technology Acceptance Model. They may even be more confident, because GPS sports watches easily record information during sports activities. In addition, Davis [27] pointed out that perceived usefulness and perceived ease of use are also affected by external variables, such as personal traits, organizational structures, and task characteristics. They also emphasized that external variables can be regarded as indirect factors affecting behavioral intentions. In this study, people's attitudes towards GPS sports watches do not always remain the same, which varies with the changes of external factors. For example, ordinary people may only focus on recording sports time, mileage, or heart rates through GPS sports watches. However, professional athletes or mountain guides are more likely to force themselves to learn other advanced functions of GPS sports watches to help their professions or careers. After mastering the functions, they will be more willing to use GPS sports watches. As TAM has been applied in industries, its shortcomings have gradually appeared. According to Venkatesh and Davis [9], in many studies, TAM can only explain 40% of the variables in behavioral intention to use and usage behaviors and ignores factors, such as personal values, habits, and social influences. Thus, they proposed an extension of the technology acceptance model (TAM2) and considered that social influence processes and cognitive instrumental processes have certain effects on perceived usefulness. Social influence processes have three dimensions: subjective norm, voluntariness, and image. Meanwhile, cognitive instrumental processes have four dimensions: job relevance, output quality, result demonstrability, and perceived ease of use. Moderating variables include voluntariness and experience. Venkatesh and Davis further [9] explained these seven dimensions.

(1) Subject Norm: this dimension includes "internalization" and "identity" and affects perceived usefulness, indicating that important people affect the degree to which they use information systems
(2) Image: the degree to which users consider that using a new information technology system will enhance their social status
(3) Job Relevance: the degree to which users consider that their jobs can utilize an information system
(4) Output Quality: the degree to which users consider the good effects of an information system after fulfilling their task requirements
(5) Result Demonstrability: the result specificity that users consider after using an information system
(6) Experience: users' experience infusing an information system
(7) Voluntariness: the degree of active acceptance rather than passive acceptance in the process of using an information system

The above definitions show the effects of social influence processes and cognitive instrumental processes, thereby extending, explaining, and improving the explanatory ability of the theoretical model.

2.3. Hypothetico Deductive. For sports enthusiasts, GPS sports watches are in demand. According to Chen [28], the visual interface design of Apple Watches and ASUS's sports watches is better than Garmin's. Garmin reduces levels and is designed with low-resolution pixels to make the integral color and screen luminance more suitable for use in the sun to achieve low power consumption. People are more confident in the interface operation of Garmin, because the overall information architecture is simple and clear. In other words, GPS sports watch users have different requirements for result demonstrability and output quality of different brands of sports watches. According to the literature review, output quality has effects on perceived usefulness. The good effects of information systems in meeting task requirements make users subjectively consider that this technology is helpful for job performance and the future [29–31]. Thus, this paper proposes Hypothesis I: output quality has significant effects on perceived usefulness. Further, the significantly positive effects of result demonstrability on perceived usefulness are verified by some studies. After information systems are used, the result demonstrability makes users subjectively consider that this technology is helpful for job performance and the future [30, 32]. Thus, this paper proposes Hypothesis II: result demonstrability has significant effects on perceived usefulness. Some studies show that perceived ease of use has significantly positive effects on perceived usefulness. The easier users perceive the technology is to be used, the more confident they are in self-efficacy and self-control, and the more positive their attitudes are towards systems, making them subjectively consider that this technology is helpful for job performance and the future [33, 34]. Thus, this study proposes Hypothesis III: perceived ease of use has significant effects on perceived usefulness. On the other hand, some studies support that perceived ease of use has significantly positive effects on behavioral intention to use. The easier users perceive the technology is to be used, the more confident they are in self-efficacy and self-control, and the more positive their attitudes are towards systems, thus affecting their intention to use this technology [35–37]. Still, other studies argue that perceived usefulness has significantly positive effects on behavioral intention to use [25, 38–40].

3. Research Method

3.1. Research Framework. This study aims to explore the effects of output quality and result demonstrability on the perceived usefulness of GPS sport swatches from the perspective of Industry 4.0. The research architecture proposed based on the research purposes and literature is shown in Figure 1.

3.2. Research Respondents. With 2020 Taiwan International Triathlons participants as the research respondents, this study has a sampling error of no more than 4.5% and a confidence interval of 95%. The present study set the sample number as 280 and conducted a random sampling outside the 2020 Taiwan International Triathlons from November 14th to November 15th, 2020. A total of 270 valid questionnaires were obtained after the questionnaires were returned, and the invalid ones were omitted, attaining a valid response rate of 92%.

3.3. Research Instruments. The questionnaire of this study, developed based on the study and questionnaire of Guo (2013), consists of three parts with 23 items, including 9 on basic personal information, 10 on TAM, and 4 on cognitive promotion. A five-point Likert scale is used in this study, and each item is scored from 1 (strongly disagree) to 5 (strongly agree).

3.4. Data Processing and Analysis. In this study, the valid questionnaires are counted, while invalid questionnaires are removed. The statistical software SPSS 23.0 is used to create

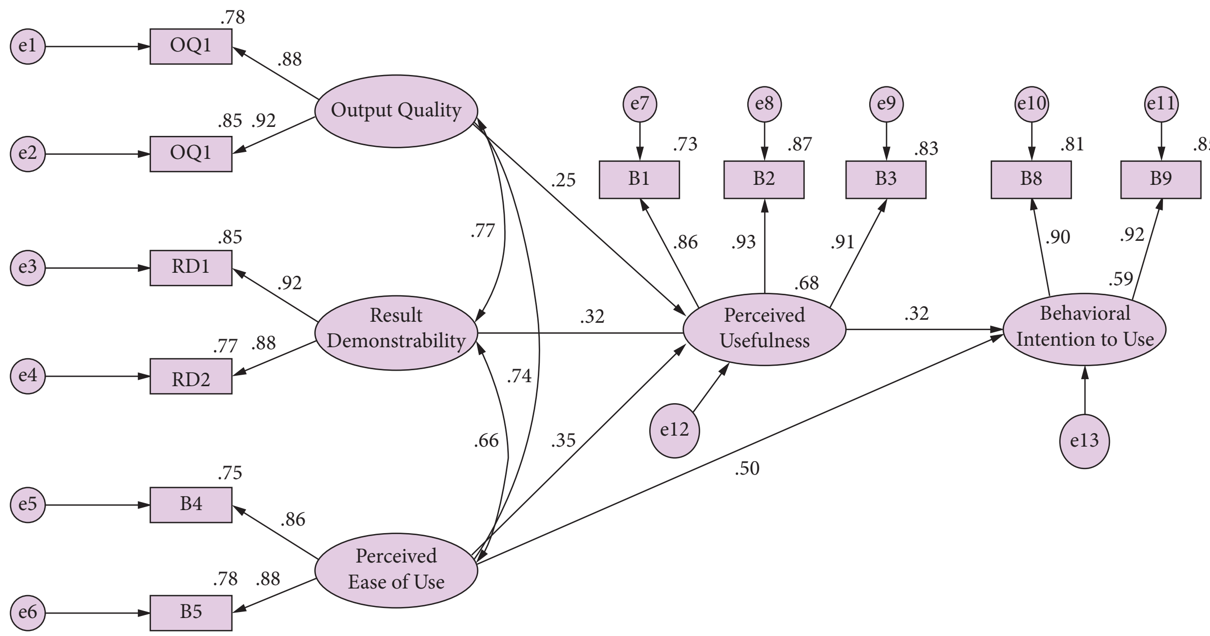


Figure 1: Effects of output quality and result demonstrability on the perceived usefulness of GPS sports watches from the perspective of industry 4.0.

files based on the data, and the demographic variables are analyzed through descriptive statistics. On the other hand, the statistical software AMOS 23.0 is used for path analysis of the correlation among variables.

4. Research Results

4.1. Sample Characteristics. In this study, the participants of the Taitung international triathlon are taken as test samples with a total of 250 valid samples. In terms of gender, there are 184 males, accounting for 73.6% of the valid samples, and there are 66 females, accounting for 26.4%. In terms of age, 99 people are between 30 and 39, accounting for 39.6% of the valid samples, and 6 people are less than 19 years old, accounting for 2.4%. In terms of the "participant" category, 117 respondents took part in the half triathlon, accounting for 46.8% of the valid samples. Meanwhile, 26 people participated in the "others" category, accounting for 10.4% of the valid samples. In terms of occupation, 92 respondents were students, which comprise the majority of the samples, accounting for 36.8% of the valid samples. On the other hand, 10 respondents were teachers, being the least, accounting for 4.0% of the valid samples. In terms of the educational level, 150 people have university (college) degree, accounting for 60% of the valid samples, and 19 people are below the senior high (higher vocational) school level, accounting for 7.6%. In terms of income, 130 people earn more than NT$50,001per month, accounting for 52.0% of the valid samples, and 23 people earn more than NT$20,001 and less than NT$30,000 per month, accounting for 9.2%. In terms of the number of competitions participated, 121 people have taken part in two to five competitions, accounting for 48.4% of the valid samples, and 28 people have taken part in more than 11 competitions, accounting for 11.2%. In terms of training hours, 92 people train irregularly, accounting for 36.8% of the valid samples, and 5 people train over 21 hours per week, accounting for 2.0%. In terms of sports seniority before purchasing GPS sports watches, 83 people have been exercising for four to five years, accounting for 33.2% of the valid samples, and 48 people have been exercising in less than one year, accounting for 19.2%. Table 1 lists the samples' characteristics.

4.2. Measurement Model Analysis. In this study, the reliability and validity of the questionnaire are verified by Catalysis, items are corrected based on the modification indices (M.I.), and items B6, B7, and B10 of the TAM scale are deleted.

4.2.1. Verification of Convergent Validity. Bagozzi and Yi [41] pointed out that convergent validity verification mainly verifies the composite reliability (C.R.) and the average variance extracted (AVE) of questionnaire dimensions. They suggested that C.R. and AVE should be greater than 0.6 and 0.5, respectively, to achieve good convergent validity [42]. In this study, the convergent validity of perceived usefulness and perceived ease of use is verified from the dimensions of behavioral intention to use, output quality, and result demonstrability. The verification results show that the factor loadings of all dimensions are between 0.78 and 0.93, C.R. is between 0.87 and 0.91, and AVE is between 0.77 and 0.82, satisfying the convergent validity criteria recommended by [41–43]. This indicates that the questionnaire in this study has good convergent validity, as shown in Tables 2–4.

4.2.2. Discriminate Validity. In this study, the discriminate validity is verified by the confidence interval method (bootstrap). This study first establishes the confidence

Table 1: Tester characteristics.

Variables	Categories	Tester characteristics	Percentage (%)	Cumulative percentage (%)
Gender	Male	184	73.6	73.6
	Female	66	26.4	100.0
Age	Under 19 years old	6	2.4	2.4
	20–29 years old	48	19.2	21.6
	30–39 years old	99	39.6	61.2
	40–49 years old	77	30.8	92.0
	Above 50 years old	20	8.0	100.0
Participant category	Half triathlon	117	46.8	46.8
	Full triathlon	45	18.0	64.8
	Standard triathlon	62	24.8	89.6
	Others	26	10.4	100.0
Occupation	Military personnel	13	5.2	5.2
	Civil servants	19	7.6	12.8
	Teachers	10	4.0	16.8
	Businessmen	85	34.0	50.8
	Farmers	31	12.4	63.2
	Students	92	36.8	100.0
Educational level	Below senior high (higher vocational) school level	19	7.6	7.6
	University (college) degree	150	60.0	67.6
	Above graduate school level	81	32.4	100.0
Monthly income	Less than NTD 20,000	32	12.8	12.8
	NTD 20,001–30,000	23	9.2	22.0
	NTD 30,001–40,000	35	14.0	36.0
	NTD 40,001–50,000	30	12.0	48.0
	More than NTD 50,001	130	52.0	100.0
Number of participations	Once	71	28.4	28.4
	2–5 times	121	48.4	76.8
	6–10 times	30	12.0	88.8
	More than 11 times	28	11.2	100.0
Training hours	Irregular sports	92	36.8	36.8
	Less than 6 hours per week	51	20.4	57.2
	7–12 hours per week	77	30.8	88.0
	13–20 hours per week	25	10.0	98.0
	More than 21 hours per week	5	2.0	100.0
Sports seniority before the purchase of GPS sports watches	Less than 1 year	48	19.2	19.2
	2-3 years	70	28.0	47.2
	4-5 years	83	33.2	80.4
	More than 6 years	49	19.6	100.0

Table 2: Technology acceptance model confirmatory factor analysis.

Dimensions	Indices	Standardized loadings	Nonstandardized loadings	S.E.	C.R. (*t*-value)	*P*	SMC	C.R.	Ave
Perceived usefulness	B1	0.78	1.00				0.60	0.91	0.77
	B2	0.93	1.11	0.07	16.76	***	0.87		
	B3	0.92	1.05	0.07	16.00	***	0.85		
Perceived ease of use	B4	0.86	1.00				0.73	0.87	0.77
	B5	0.90	1.07	0.07	15.81	***	0.81		
Behavioral intention to use	B8	0.90	1.00				0.81	0.90	0.82
	B9	0.92	1.03	0.06	18.09	***	0.85		

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

interval for Pearson's correlation coefficient among dimensions and then tests whether it contains 1 to determine if the dimensions are completely correlated. According to the results, the confidence interval among dimensions does not contain 1, indicating discriminate validity among dimensions in this study [44], as shown in Tables 5 and 6.

Table 3: Output quality confirmatory factor analysis.

Dimensions	Indices	Standardized loadings	Nonstandardized loadings	S.E.	C.R. (t-value)	P	SMC	C.R.	Ave
Output quality	OQ1	0.85	1.00				0.72	0.88	0.79
	OQ2	0.93	1.03	0.06	17.89	***	0.86		

Table 4: Result demonstrability confirmatory factor analysis.

Dimensions	Indices	Standardized loadings	Nonstandardized loadings	S.E.	C.R. (t-value)	P	SMC	C.R.	Ave
Result demonstrability	RD1	0.90	1.00				0.82	0.89	0.81
	RD2	0.90	0.99	0.05	19.74	***	0.81		

$^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

Table 5: 95% confidence interval for bootstrap correlation coefficient of the technology acceptance model.

Parameters			Estimates	Bias-corrected		Percentile method	
				Lower bound	Upper bound	Lower bound	Upper bound
Perceived usefulness	<-->	Perceived ease of use	0.74	0.62	0.85	0.61	0.84
Perceived usefulness	<-->	Behavioral intention to use	0.68	0.54	0.79	0.54	0.79
Perceived ease of use	<-->	Behavioral intention to use	0.71	0.58	0.83	0.57	0.82

Source: Compiled by this study.

Table 6: 95% confidence interval for bootstrap correlation coefficient of the Output Quality model.

Parameters			Estimates	Bias-corrected		Percentile method	
				Lower bound	Upper bound	Lower bound	Upper bound
Output quality	<-->	Result demonstrability	0.77	0.58	0.91	0.60	0.92

Source: Compiled by this study.

4.2.3. Structural Model Analysis. According to the standards recommended by Hair et al. [43] in the structural model analysis, this study tests the overall model fit by 7 indices: chi-square value (χ^2), the ratio of χ^2 to degrees of freedom, GFI, AGFI, RMSEA, CFI, and PCFI. The corrected ratio of χ^2 to degrees of freedom is 1.94, which is consistent with the suggestion of Bagozzi and Yi [41] that the ratio of χ^2 to degrees of freedom should be as small as possible. Hair et al. [43] described that GFI and AGFI should be as close as possible to 1, respectively, 0.95 and 0.91 after correction in this study. The corrected RMSEA in this study is 0.06, which conforms to the suggestion of Browne and Cudeck [45] that RMSEA should be less than 0.08. While the standard CFI should be larger than 0.90, the corrected CFI in this study is 0.99. On the other hand, while PCFI should be at least larger than 0.50, the corrected PCFI in this study is 0.65, which meets the recommended standard [46, 47]. Such results indicate that the overall fit indices are within the acceptable range and that the model is acceptable, as shown in Table 7.

Empirical results of research hypotheses.

4.3. Results. At the end of this study, the results of statistical analysis are compared with those of previous literature, and the results of hypothesis verification are discussed below. As shown in Table 7, output quality has significantly positive effects on perceived usefulness, result demonstrability has significantly positive effects on perceived usefulness, perceived ease of use has significantly positive effects on perceived usefulness, perceived ease of use has significantly positive effects on behavioral intention to use, and perceived usefulness has significantly positive effects on behavioral intention to use.

4.4. Discuss. According to Table 8, H1 is true—that is, output quality has significantly positive effects on perceived usefulness. This result is the same as that of Lee et al. [29], possibly because triathlon athletes believe that GPS sports watches can provide correct data and information and consider GPS sports watches to be helpful for training and competition. Further, H2 is also true—that is, result demonstrability has significantly positive effects on perceived usefulness. This conclusion is similar to that of Chang [32], possibly because the data provided by GPS sports watches make it easier for triathlon athletes to record their performance or adjust their training plans; hence, GPS sports watches are found to be helpful. On the other hand, H3 is true—that is, perceived ease of use has significantly positive effects on perceived usefulness. This result is similar to that of Lu and Lo [34], possibly because triathlon athletes have positive attitudes towards GPS sports watches if their training results improve feruling. Meanwhile, H4 is also true—that is, perceived ease of use has significantly positive

Table 7: Overall model fit analysis.

Fit indices	Permissible range	Correction model	Model fit discrimination
χ^2 (chi-square)	As small as possible	69.9	
Ratio of χ^2 to degree of freedom	<3	1.94	Passed
GFI	>0.80	0.95	Passed
AGFI	>0.80	0.91	Passed
RMSEA	<0.08	0.06	Passed
CFI	>0.90	0.99	Passed
PCFI	>0.50	0.65	Passed

Table 8: Empirical results of research hypotheses.

Hypotheses	Path relationship	Path value	Validity of hypotheses
1	Output quality ⟶ perceived usefulness	0.25	Valid
2	Result demonstrability ⟶ perceived usefulness	0.32	Valid
3	Perceived ease of use ⟶ perceived usefulness	0.35	Valid
4	Perceived ease of use ⟶ behavioral intention to use	0.50	Valid
5	Perceived usefulness ⟶ behavioral intention to use	0.32	Valid

effects on behavioral intention to use. This result is similar to that of Malik and Annuar [35], possibly because triathlon athletes are more willing to use GPS sports watches due to their effects on competition and training results. Lastly, H5 is true—that is, perceived usefulness has significantly positive effects on behavioral intention to use. This conclusion is similar to that of Ünal and Uzun [39], possibly because triathlon athletes believe that GPS sports watches are helpful to them and are more confident in such devices.

5. Conclusion and Suggestions

5.1. Suggestions

5.1.1. For Triathlon Participants. According to the results, output quality has significantly positive effects on perceived usefulness. With the advent of Industry 4.0 intelligent manufacturing, intelligent products have the advantages of information and communication by combining with big data. Therefore, it is suggested that triathlon participants first confirm the correct settings of their GPS sports watches to get the correct output quality. For example, in measurement settings, correct units, such as meter or feet, should be chosen to conform to the custom in the user area, or hap, mbar, or mmHg should be set first as the unit of air pressure. In addition, missteps sports watches have built-in orientation, altitude, and air pressure sensors—that is, ABC sports watches contain altimeters, barometers, and compasses. Therefore, before triathlon training or competition, it is necessary to clearly understand the principle of sensor calibration and calibrate sensors in advance. Because this is important to output quality, error settings, failure to calibrate, or after-event incorrect training and competition information may reduce the efficacy of GPS sports watches or the willingness to use them. Therefore, it is suggested that triathlon participants frequently or regularly correct GPS errors at the height of their current positions. For example, height information can be obtained through maps and local height indicators and then be manually input for correction to reduce the differences between the values obtained by GPS sports watches and the local elevations. Thus, the data obtained can be used as an ineffective reference for training and competition.

According to the results of this study, perceived usefulness also has significantly positive effects on behavioral intention to use. Hence, it is suggested that triathlon participants have a deep understanding of the correct use of GPS sports watches to improve their sports and training results effectively. For example, the data measured by optical heart rate monitoring devices are significant for triathlon participants since heart rate zones help determine training intensity. Thus, triathlon participants are suggested to avoid wearing such devices over their wrists to prevent inaccurate values caused by loose space between skin and optical heart rate meters. In addition, before training or competition, it is suggested to warm up to promote blood circulation, which will help GPS sports watches read heart rates more accurately and properly play their roles.

The results also show that result demonstrability has significantly positive effects on perceived usefulness. Hence, it is suggested that triathlon participants improve their abilities to understand technological information to make the results collected by GPS sports watches easy to observe and use. For example, in terms of technological resources of GPS sports watches (such as software and hardware supporting GPS sports watches, extended devices, and social media applications), if people are familiar with innovative information technologies, such as Strata or Relive APP, GPS sports watches can become training partners and improve personal training results.

5.1.2. For GPS Sports Watch Research and Development Manufacturers. According to the empirical results, perceived ease of use has significantly positive effects on perceived usefulness. Hence, under the future development trend of Industry4.0, it is suggested that GPS sports watch research and development manufacturers design hardware and software according to ergonomic standards to achieve a logical and human-based operation process of GPS sports watches. In addition, simple product interfaces and operations should be developed to make it easy for triathlon participants to use the devices and focus on training and competition. Furthermore, Industry 4.0 is the future trend for combining big data analysis and cloud computing to bring people into a smart life. In particular, social networks are flourishing, and "sharing" makes sports more interesting. Therefore, GPS sports watch research and development manufacturers should enable users to easily upload or share information through the simplest operations. For example, by combining GPS sports watches with sports APPs, training routes and tracks can be drawn and used with photos and text to contribute to triathlon networks. In addition, some triathlon participants can cross-train physically through other sports, such as cross-country running and mountaineering. Therefore, when GPS sports watches are combined with offline maps or built-in Taiwan hiking route maps, they can enable triathlon participants to know their locations even without the Internet or be integrated with others' tracks to serve as a reference. These designs can be considered good tools in diversifying training. In other words, if GPS sports watches are easy to use, they will be useful tools for triathlon participants to obtain the correct information and appropriate assistance.

According to the results, perceived ease of use has significantly positive effects on behavioral intention to use. Therefore, it is suggested that, in addition to designing easy-to-operate interfaces, GPS sports watch research and development manufacturers consider classifying GPS sports watches as functional watches. Users with fixed exercise habits should also emphasize sport straining records and analysis. Considering that this is a niche market, the consumer base is not as wide as that of smart bracelets. Therefore, if GPS sports watch research and development manufacturers can make innovations in watch functions and make good use of online sports communities to retain users, the stickiness of GPS sports watch users can be improved, and their willingness to continue to use these devices can be enhanced.

5.1.3. For Future Studies. With triathlon participants as the research subjects, this paper conducts empirical research based on the theory of the extended technology acceptance model and explores the practical use of GPS sports watches and future research and development directions. However, through a comprehensive view of the current GPS sports watch market, it is important that products be highly recognized by consumers, offer assistance for users in sports, and produce different values. At present, the GPS sports watch market seems to have achieved the goal of having its products perceived as a matter of wants. However, there is still room for improvement before users could perceive it as a need. Therefore, closeness to users' living habits and bringing new values can effectively improve product stickiness. The construction of value focuses on users' intrinsic motivation to pursue happiness and fun, rather than the extrinsic motivation emphasized for perceived usefulness and ease of use in the past. Therefore, it is suggested that the third-generation technology acceptance model be used for future empirical studies.

In addition to the two variables of the extended TAM, namely, social influence process and cognitive instrumental process, "positioning" and "system adaptability" are incorporated into the third-generation TAM, including perceived enjoyment classified into system adaptability. Under the future development of Industry 4.0, creating fun at using GPS sports watches, making them entertaining, keeping users curious, and stimulating strong internal motivation will help enterprises understand the development trend of these products and the usage habits of future consumers.

5.2. Research Limitations

(1) In this study, a questionnaire survey is conducted among the 2020 Taitung International Triathlon participants by purposive sampling. Thus, the integrity of sample representativeness is limited.

(2) In the extended TAM theory, experience is also an interfering variable affecting perceived usefulness. Most respondents in this study do not have rich experience in GPS sports watches, making it difficult to determine the interference of experience unperceived usefulness.

(3) Research contributions: this study employed an extended technology acceptance model to explain the effects of "output quality" and "result demonstrability" on "perceived usefulness" and explored the behavior and experience of wearable sports devices that adopt new technologies. According to this study, product adhesion can be effectively improved by staying close to users' living habits and bringing new values. The "value" construction can skip past extrinsic motivation that emphasizes perceived usefulness and perceived ease of use and focus instead on the intrinsic motivation of users for happiness and fun. Therefore, the third-generation technology acceptance model can be used in future empirical studies. In addition to the two variables of social influence process and cognitive instrumental process of the extended technology acceptance model, an additional two variables, "positioning" and "system adaptability," were added to the third-generation technology acceptance model. Perceived enjoyment was classified into system adaptability to strengthen the integrity of the technology acceptance model, further explain the extension, and improve the explanatory ability of the theoretical model in order to understand users' behavioral intention of information technology.

5.3. Conclusion. As wearable devices become more mature, consumer demands for functions and efficiency have changed, encouraging manufacturers to constantly make innovations. In the wave of Industry 4.0, GPS sports watches certainly will develop towards digitization and intelligence. Whether the information is correct and real-time, operation interfaces easy to use and the displayed information easy to understand have become issues that consumers and manufacturers emphasize, showing the important role the GPS sports watches play in output quality in the future. Therefore, from the perspective of Industry 4.0, this study investigates the effects of output quality and result demonstrability of GPS sports watches on perceived usefulness.

Data Availability

The data are available upon request to the authors. The data source is obtained from the questionnaire analysis of the author's research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] Y. C. Wang and T. H. Chiang, "Information management software technology for asset digitalization in industrial 4.0 application," *Journal of the Techtronic Industry*, vol. 437, pp. 23–31, 2019.

[2] C. N. Wang and Y. L. Ma, "International development trend of industry 4.0 and Taiwan's response measures," *International Financial Reference Data*, vol. 69, pp. 133–155, 2016.

[3] F. S. Ho, *Industry Model and Influence of Industry 4.0*, p. 454, Far Eastern Magazine, Taipei, Taiwan, 2015.

[4] K. F. Lin, "A study on Taiwan's runners purchase motivation of wearable device," Master's thesis, Department of Physical Education, National Taiwan Normal University, Taipei, Taiwan, 2017.

[5] Garnet, "Gartner forecasts global spending on wearable devices to total $81.5 billion in 2021," 2021, https://www.gartner.com/en/newsroom/press-releases/2021-01-11-gartner-forecasts-global-spending-on-wearable-devices-to-total-81-5-billion-in-2021.

[6] P. H. Chen, *Amazon's Intelligent Health Layout Fromthe Smart BraceletHalo*, Market Intelligence & Consulting Institute, Institute for Information Industry, Taipei, Taiwan, 2021.

[7] Sports Administration, "2020 sports statistics," 2020, https://www.sa.gov.tw/Resource/Ebook/637499473534004656.pdf.

[8] A. Shcherbina, C. M. Mattsson, D. Waggott et al., "Accuracy in wrist-worn, sensor-based measurements of heart rate and energy expenditure in a diverse cohort," *Journal of Personalized Medicine*, vol. 7, no. 2, pp. 1–12, 2017.

[9] V. Venkatesh and F. D. Davis, "A theoretical extension of the technology acceptance model: four longitudinal field studies," *Management Science*, vol. 46, no. 2, pp. 186–204, 2000.

[10] C. Schultze and S. Burr, "Market research on garment-based "wearables" and biophysical monitoring and a new monitoring method," *Studies in Health Technology and Informatics*, vol. 108, pp. 111–117, 2004.

[11] P. Düking, M. Tafler, B. Wallmann-Sperlich, B. Sperlich, and S. Kleih, "Behavior change techniques in wrist-worn wearables to promote physical activity: content analysis," *JMIR mHealth and uHealth*, vol. 8, no. 11, Article ID e20820, 2020.

[12] Y. P. Su and H. S. Wang, "Energy expenditure evaluation of Mt. Qixing Xiaoyoukeng trail: the accuracy of wearable devices," *Physical Education Journal*, vol. 53, no. 2, pp. 179–187, 2020.

[13] P. Düking, L. Giessing, M. O. Frenkel, K. Koehler, H. C. Holmberg, and B. Sperlich, "Wrist-Worn wearables for monitoring heart rate and energy expenditure while sitting or performing light-to-vigorous physical activity: validation study," *JMIR mHealth and uHealth*, vol. 8, no. 5, Article ID e16716, 2020.

[14] Y. C. Yang, H. Peng, and L. W. Hsieh, "A study on the effects of road running participation on runners' willingness to purchase wearable sports devices," *Taiwan Journal of Sports Scholarly Research*, vol. 63, pp. 25–41, 2017.

[15] C. M. Lee and D. H. Lee, "The study of key factors affecting consumers' decisions on purchasing wearable devices using the AHP method," *Management Research*, vol. 17, pp. 87–123, 2017.

[16] P. Shambrook, P. J. Lander, and O. Maclaren, "A study into the reliability of the data flow from GPS enabled portable fitness devices to the Internet," *International Journal of Exercise Science*, vol. 11, no. 7, pp. 1184–1193, 2018.

[17] M. J. Tsai and Y. M. Chuang, "Research on personal health status of the master with mobile device," *Journal of Data Analysis*, vol. 14, no. 5, pp. 39–71, 2019.

[18] Y. J. Chen, C. H. Chang, M. S. Wang, and L. T. Lu, "Effects of exergaming on physical activity: a review of the literature," *Chung Yuan Physical Education Journal*, vol. 13, pp. 17–27, 2019.

[19] Y. C. Chou and H. J. Lee, "Exploring basketball load in positional difference and training scenario by wearable device," *Physical Education Journal*, vol. 53, no. 3, pp. 315–326, 2020.

[20] T. H. Davenport and L. Prusak, *Working Knowledge: Managing what Your Organization Knows*, Harvard Business School Press, Boston, MA, USA, 1988.

[21] C. Lee, *Industrial Big Data: Intelligent Transformation and Value Innovation in Industry 4.0 Era*, Common Wealth Magazine, Taipei, Taiwan, 2016.

[22] C. M. Hsiung, "The application solution for industry 4.0 in Germany, China and taiwan," *Journal of the Mechatronic Industry*, vol. 406, pp. 20–28, 2017.

[23] H. D. Hsu, "Opinions on occupational safety issues of industry 4.0and coping strategies," *Industrial Safety and Hygiene*, vol. 379, pp. 32–42, 2021.

[24] Executive Yuan, "Productivity 4.0 initiative of the executive Yuan," 2015, https://www.nchu.edu.tw/~class/bulletin/MOE/105_MoE_re_allr.pdf.

[25] H. N. Lee, Y. F. Cheng, C. H. Chang, and J. G. Wu, "Study on attitude toward mobile devices in students with visual impairments: perceived usefulness and perceived ease of use as mediating variables," *Bulletin of Educational Psychology*, vol. 50, no. 1, pp. 107–129, 2018.

[26] I. Ajzen and M. Fishbein, "A Bayesian analysis of attribution processes," *Psychological Bulletin*, vol. 82, no. 2, pp. 261–277, 1975.

[27] F. D. Davis, "Perceived usefulness, perceived ease of use, and user acceptance of information technology," *MIS Quarterly*, vol. 13, no. 3, pp. 319–340, 1989.

[28] S. Y. Chen, *Amos Operation of Structural Equation Model*, San Ming Book Company Ltd., Taipei, Taiwan, 1st edition, 2007.

[29] W. H. Lee, C. W. Lin, C. W. Lin, and K. H. Shih, "A technology acceptance model for the perception of restaurant service robots for trust, interactivity, and output quality,"

International Journal of Mobile Communications, vol. 16, no. 4, pp. 361–376, 2018.

[30] M. Ismail, E. Çelebi, and H. Nadiri, "How student information system influence students' trust and satisfaction towards the university? An empirical study ina multicultural environment," *IEEE Access*, vol. 7, 2019.

[31] C. H. Lee, "The technology acceptance of members of public sector for knowledge management," Master's thesis, Institute of Public Affairs Management, National San Yat-sen University, Kaohsiung, Taiwan, 2004.

[32] Y. C. Chang, "A study of elementary school teachers' acceptance of tablet PCs in Yilan County," Master's thesis, Department of Learning and Digital Technology, Fo Guang University, Yilan City, Taiwan, 2012.

[33] D. Sugandini, Purwoko, A. Pambudi, S. Resmi, M. Reniati, and R. A. Kusumawati, "The role of uncertainty, perceived, ease of use, and perceived usefulness toward the technology adoption," *International Journal of Civil Engineering & Technology*, vol. 9, no. 4, pp. 660–669, 2018.

[34] C. Y. Lu and C. Y. Lo, "Effects of perceived risk and online banking service experience on mobile banking APP acceptance," Master's thesis, Department of Information Management, Shu-Te University, Kaohsiung City, Taiwan, 2012.

[35] A. N. A. Malik and S. N. S. Annuar, "The effect of perceived usefulness, perceived ease of use, reward, and perceived risk toward E-wallet usage intention," in *Eurasian Business and Economics Perspectives*, M. H. Bilgin, H. Danis, and E. Demir, Eds., vol. 17, Cham, Switzerland, Springer, 2021.

[36] Y. C. Tsai, *The Study of Behavior Intention to Accept the DVD Rental Machine in Technology Acceptance Model*, Department of Management Sciences, National Yang Ming Chiao Tung University, Taipei, Taiwan, 2007.

[37] H. Y. Huanh, "Extending the technology acceptance model and flow to explore the intention of mobile games," Master's thesis, Department of Marketing and Distribution Management, National Pingtung University, Pingtung City, Taiwan, 2016.

[38] A. M. Mutahar, N. M. Daud, R. Thurasamy, O. Isaac, and R. Abdulsalam, "The mediating of perceived usefulness and perceived ease of use," *International Journal of Technology Diffusion*, vol. 9, no. 2, pp. 21–40, 2018.

[39] E. Ünal and A. M. Uzun, "Understanding university students' behavioral intention to use Edmodo through the lens of an extended technology acceptance model," *British Journal of Educational Technology*, vol. 52, no. 3, 2020.

[40] H. T. Huang, C. Tsai, and D. S. Zhu, "An extension of the motivation model to explore the behavioral intention of health knowledge repository systems: technological-social-motivational perspectives," *Journal of E-Business*, vol. 11, no. 3, pp. 569–609, 2009.

[41] R. P. Bagozzi and Y. Yi, "On the evaluation of structure equations models," *Academic of Marketing Science*, vol. 16, no. 1, pp. 76–94, 1988.

[42] C. Fornell and D. F. Larcker, "Evaluating structural equation models with unobservable variables and measurement error," *Journal of Marketing Research*, vol. 18, no. 1, pp. 39–50, 1981.

[43] J. F. Hair Jr., R. E. Anderson, R. L. Tatham, and W. C. Black, *Multivariate Data Analysis*, Prentice-Hall, Englewood Cliffs, NJ, USA, 5th edition, 1998.

[44] G. Torkzadeh, X. Koufteros, and K. Pflughoeft, "Confirmatory analysis of computer self-efficacy," *Structural Equation Modeling: A Multidisciplinary Journal*, vol. 10, no. 2, pp. 263–275, 2003.

[45] M. W. Browne, R. Cudeck, K. A. Bollen, and J. S. Long, *Testing Structural Equation Models*, Sage Publications, Thousand Oaks, CA, USA, 1993.

[46] P. M. Bentler, *EQS Structural Equations Program Manual*, Multivariate Software, Encino, CA, USA, 1995.

[47] G. W. Cheung and R. B. Rensvold, "Evaluating goodness-of-fit indexes for testing measurement invariance," *Structural Equation Modeling: A Multidisciplinary Journal*, vol. 9, no. 2, pp. 233–255, 2002.

Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 3664709, 11 pages
https://doi.org/10.1155/2021/3664709

Research Article

A Novel Contractor Selection Technique Using the Extended PROMETHEE II Method

Kuei-Hu Chang [1,2]

[1] *Department of Management Sciences, Chinese Military Academy, Kaohsiung 830, Taiwan*
[2] *Institute of Innovation and Circular Economy, Asia University, Taichung 413, Taiwan*

Correspondence should be addressed to Kuei-Hu Chang; evenken2002@gmail.com

Received 25 September 2021; Revised 26 October 2021; Accepted 1 November 2021; Published 18 November 2021

Academic Editor: Ali Ahmadian

Selecting suitable contractors directly influences product quality, corporate profits, and even sustainable development. The selection problem of contractors is, therefore, a critical issue for the sustainable development of an enterprise. However, traditional contractor selection techniques are unable to handle information regarding the relative importance of criteria or handle nonexistent or missing data in the assessment process of contractor selection. In order to effectively address this problem, this study proposes a new contractor selection technique that integrates the concept of soft set and the PROMETHEE II method to select suitable contractors. Three numerical examples are applied to prove the correctness and effectiveness of the proposed technique. This study also compares the simulation results achieved using the proposed method with those achieved using the traditional weighted arithmetic averaging method and the data envelopment analysis (DEA) technique. The simulation results show that the proposed method is a more general contractor selection technique for handling incomplete information than the traditional weighted arithmetic averaging method and the DEA method.

1. Introduction

Contractor selection includes multiple performance assessment criteria and is a multicriteria decision-making (MCDM) issue. Choosing suitable contractors directly affects the competitive advantage of products and the sustainable development of enterprises. Therefore, contractor selection is a critical issue in the supply chain and has received considerable research attention. Many authors have used different computation methods to address contractor selection problems. For example, San Cristobal [1] combined VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), techniques for order preference by similarity to ideal solution (TOPSIS), and the analytical hierarchy process (AHP) methods for selecting suitable contractors for the "La Braguía" road-building project in Spain. Yang et al. [2] proposed an approach based on data envelopment analysis (DEA) that was applied to support the selection of best value contractors in single-input and multiple-output manners. Akcay et al. [3] used the concept of fuzzy logic to propose a fuzzy decision support model for contractor selection of Turkish construction projects. Hasnain et al. [4] proposed an analytical network process (ANP) based decision support system to solve the most valuable contractor selection problems in road construction projects. Chang [5] integrated the soft set and intuitionistic fuzzy weighted average methods to select the best supplier under an incomplete information environment. Gharedaghi and Omidvari [6] integrated the analytical network processing, decision-making trial and evaluation laboratory (DEMATEL), and the grey system theory to select suitable safety contractors for oil and gas industries.

The contractor selection assessment process may encounter instances of missing or nonexistent assessment criteria data. Incomplete attribute value information increases the difficulty of assessing contractors. In order to handle incomplete information, the traditional contractor selection method directly deletes incomplete attribute value information. Deleting information, however, results in a reduction in available information and distorts evaluation results. Fortunately, the soft set method is able to handle incomplete assessment criteria information. The soft set method was first proposed by Molodtsov [7] to handle the uncertainty of data or traditional mathematical tools unable to handle fuzzy information in the process of information fusion, and following the development of soft sets, numerous studies used the soft set method to handle different decision-making problems [7–20].

Contractors play a key role in successful operations and overall project performance; in addition, choosing the right contractors for a particular project is a major challenge in the supply chain. However, traditional contractor selection methods do not consider information regarding the relative importance of criteria. The preference ranking organization method for enrichment evaluation (PROMETHEE) method is one of the most commonly used techniques to solve MCDM issues. The advantages of the PROMETHEE method are that the relative importance of criteria is considered. PROMETHEE method was first introduced by Brans and Vincke [21], applied as an outranking relation technique between pairs of alternatives to solve MCDM problems. Because the PROMETHEE method's calculation is simple and it is easy to operate, numerous studies have used this method to handle decision-making problems in various fields. For example, Brankovic et al. [22] used PROMETHEE and the simplified elimination and choice translating reality (ELECTRE) approach to determine the criterion weight for selecting optimal alternative hydraulic structure solutions. Tian et al. [23] proposed an improved PROMETHEE II method based on axiomatic fuzzy set theory, which simultaneously considered the subjective preferences of experts and the objective weights of assessment criteria. The improved PROMETHEE II method considers ranking, as well as the degree of credibility of the raw data. The PROMETHEE method has been used in many fields, such as alternative locations for solar power plants [24], the assembly line sequencing problem [25], renewable energy source assessment [26, 27], credit risk assessment [28], electricity distribution utility performance assessment [29], logistics warehouse location selection [30], petrochemical industry [31], occupational health and safety [32], and cybersecurity of Industry 4.0 [33]. However, the typical PROMETHEE method cannot handle the incomplete assessment criteria information.

Recently, Yang et al. [2] introduced a DEA-based approach to support the selection of the best value contractor. However, this approach would cause a high repetition rate problem when DEA values are 100%. Moreover, this approach cannot handle cases when the needed expert data is missing or nonexistent during the information assessment process. In order to effectively resolve the above contractor selection issues, this study proposes a flexible PROMETHEE II method to deal with the contractor selection issue, which simultaneously includes complete and incomplete information. To verify the effectiveness of the proposed flexible PROMETHEE II approach, three contractor selection cases were adopted, and the simulation results were compared with the traditional weighted arithmetic averaging method and the DEA method [2].

The major contributions of this paper include the following advantages: (1) the proposed approach can handle incomplete assessment criteria information; (2) the proposed approach considers the relative importance of criteria; (3) the proposed approach considers the subjective preferences of experts; (4) the traditional weighted arithmetic average approach and DEA method can be viewed as special cases of the proposed approach; and (5) the proposed approach provides a more flexible contractor selection technique to support contractor assessment for selection.

The remainder of this paper is arranged as follows. Section 2 reviews related research on the PROMETHEE II method and soft set method. Section 3 introduces the proposed novel contractor selection approach for solving best-value tendering selection problems. Three contractor selection case projects are adopted, and the comparison with other related methods are discussed in Section 4. Finally, the conclusion is given in Section 5.

2. Preliminaries

This section presents some fundamental definitions and concepts related to the PROMETHEE II method and soft set.

2.1. PROMETHEE II Method. Brans and Vincke [21] proposed the PROMETHEE II approach that based on the pairwise comparison of alternatives for each criterion to solve MCDM problems. Two types of information are required for the PROMETHEE II approach: (1) the relative importance of the criteria and (2) decision-maker's preference function for comparing alternative contributions [34, 35].

The PROMETHEE II method consists of five steps [36]:

Step 1: normalize the decision matrix

$$R_{ij} = \frac{\left[x_{ij} - \min\left(x_{ij}\right)\right]}{\max\left(x_{ij}\right) - \min\left(x_{ij}\right)} \quad (i = 1, 2, \ldots n; j = 1, 2, \ldots, m), \tag{1}$$

where x_{ij} is the performance index of the i^{th} alternative of the j^{th} criterion.

For nonbeneficial criteria, equation (1) can be rewritten as follows:

$$R_{ij} = \frac{\left[\max\left(x_{ij}\right) - x_{ij}\right]}{\max\left(x_{ij}\right) - \min\left(x_{ij}\right)} \quad i = 1, 2, \ldots n; j = 1, 2, \ldots, m. \tag{2}$$

Step 2: calculate the preference function, $P_j(a,b)$ as follows:

$$P_j(a, b) = 0 \text{ if } \quad R_{aj} \leq R_{bj}, \tag{3}$$

$$P_j(a,b) = \left(R_{aj} - R_{bj}\right) \text{ if } \quad R_{aj} > R_{bj}. \tag{4}$$

Step 3: calculate the aggregated preference function, $\pi(a,b)$ as follows:

$$\pi(a,b) = \sum_{j=1}^{m} w_j P_j(a,b), \tag{5}$$

where w_j is the weight of the j^{th} criterion.

Step 4: calculate the entering flow, leaving flow, and net flow for each alternative

$$\varphi^-(a) = \frac{1}{m-1}\sum_{b=1}^{m} \pi(b,a), \tag{6}$$

$$\varphi^+(a) = \frac{1}{m-1}\sum_{b=1}^{m} \pi(a,b), \tag{7}$$

$$\varphi(a) = \varphi^+(a) - \varphi^-(a), \tag{8}$$

where $\varphi^-(a)$, $\varphi^+(a)$, and $\varphi(a)$ represent the entering flow, leaving flow, and net flow for each alternative, respectively.

Step 5: determine the ranking of all the possible alternatives.

All possible alternatives are ranked according to the net flow value $\varphi(a)$, with a higher net flow value $\varphi(a)$ representing a better alternative.

2.2. Soft Set. The soft set method is a novel mathematical method developed by Molodtsov [7] to handle the related issues of uncertain and ambiguous data, and the method is explained as follows: assume U indicates an initial universe and E be the parameters set related to the objects in U. The set $P(U)$ be the power set of U and $A \subseteq E$.

Definition 1. [7, 37]: A pair (F, A) is called a soft set (on U), where F is a mapping given by $F\colon A \longrightarrow P(U)$.

In other words, the soft set over U is a parameterized family of universe U subsets.

Definition 2. [7, 38]: Both two soft sets (F, X) and (G, Y) are in a common universe U, and (F, X) is the soft subset of (G, Y), represented as $(F, X)\,\widetilde{\subset}\,(G, Y)$, if

(i) $X \subseteq Y$ and

(ii) $\forall e \in X$, $F(e) \subseteq G(e)$.

Definition 3. [38, 39]: Both two soft sets (F, X) and (G, Y) are in a common universe U, where the union of (F, X) and (G, Y) is represented as (H, Z), and the following conditions are satisfied:

(i) $Z = X \cup Y$ and

(ii) $\forall e \in Z$, $H(e) = \begin{cases} F(e), & \text{if } e \in X - Y, \\ G(e), & \text{if } e \in Y - X,. \\ F(e) \cup G(e), & \text{if } e \in X \cap Y. \end{cases}$

Definition 4. [38, 39]: Both two soft sets (F, X) and (G, Y) are in a common universe U, where the intersection of (F, X) and (G, Y) is represented as (H, Z), and the following conditions are satisfied:

(i) $Z = X \cap Y$ and

(ii) $\forall e \in Z$, $H(e) = F(e)$ or $G(e)$.

3. The Proposed Novel Contractor Selection Method

Government procurement in Taiwan involves two principles for contractor selection: the best value bid and the lowest bid. The assessment criteria for the best value bid simultaneously include qualitative and quantitative data and present a complicated MCDM problem. However, the traditional contractor selection approach does not consider the relative importance of criteria or subjective preferences of experts. Moreover, instances may occur in the contractor selection assessment process in which assessment criteria data are missing or nonexistent. This will make the contractor selection evaluation more complicated and difficult. In order to effectively address this problem, this paper proposes a flexible PROMETHEE II method to deal with contractor selection problems, which simultaneously includes complete and incomplete information. This study uses the weighted arithmetic averaging method to fill in incomplete assessment criteria score data. Furthermore, this study applies the PROMETHEE II method to handle information about the relative importance of criteria and subjective preferences of experts. This study integrates the PROMETHEE II method and soft set method to select suitable contractors. The results are more suitably and flexibly reflect the actual situation. The implementation steps of the proposed novel contractor selection approach are as follows (depicted in Figure 1):

Step 1: confirm the bidding document assessment criteria.

Determine the content of assessment criteria according to the requirements of the actual bidding documents.

Step 2: determine the relative weights of the assessment criteria.

etermine the relative weights of the assessment criteria according to the importance level of the assessment criteria.

Step 3: determine the scores of the assessment criteria for each bidder.

Each committee member determines the assessment criteria scores for each bidder.

Step 4: fill in incomplete assessment criteria score data.

If the assessment criteria scores are incomplete, use the weighted arithmetic average approach to fill in incomplete assessment criteria score data.

Step 5: normalize the decision matrix.

Use equations (1) and (2) to compute the normalized decision matrix.

Step 6: compute the preference function $P_j(a,b)$.

Use equations (3) and (4) to compute the preference function $P_j(a,b)$.

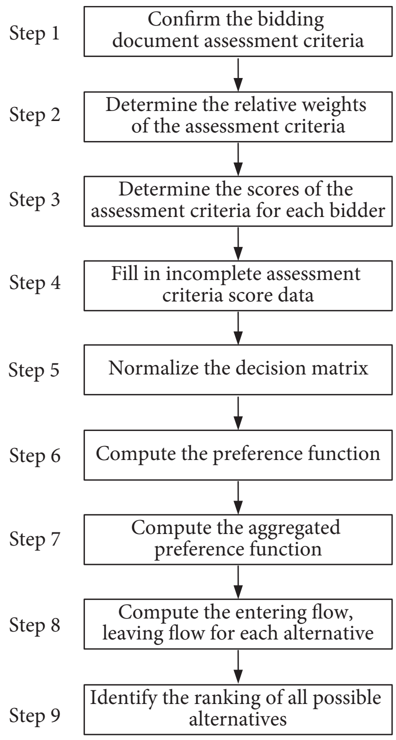


Figure 1: Flowchart of the proposed novel contractor selection method.

Step 7: compute the aggregated preference function $\pi(a, b)$.

Use equation (5) to compute the aggregated preference function $\pi(a, b)$.

Step 8: compute the entering flow and leaving flow for each alternative.

Use equations (6)–(7) to compute the entering flow and leaving flow for each alternative.

Step 9: identify the ranking of all possible alternatives.

Use equation (8) to compute the net flow values for each alternative. Rank the net flow $\varphi(a)$ from highest to lowest, with a higher net flow value $\varphi(a)$ representing a better bidder.

4. Illustrative Example

4.1. Case Project 1. This section presents an illustrative example of software supplier selection adapted from Yang et al. [2] who proved the effectiveness of the proposed novel contractor selection approach. The case company must select the optimal software supplier in order to develop and plan the management information system. There were six bidders, and a bid opening committee that consisted of four committee members in this software supplier case. The assessment criteria included the comprehension degree for the project (C1), system design and planning (C2), coding ability of a system (C3), management ability of project (C4), and past achievements and experience (C5). The relative weights of the five evaluation criteria were 0.10, 0.30, 0.30, 0.20, and 0.10, respectively. The five evaluation criteria were then used by the final bid opening committee to determine the most suitable software supplier. The five assessment criteria scores for each bidder are listed in Table 1.

4.1.1. Solution by the Traditional Weighted Arithmetic Averaging Approach. The traditional weighted arithmetic averaging approach is one of the simplest and most commonly used aggregation operators, and it can be explained as follows.

Definition 5. [40, 41]: A weighted arithmetic averaging (WAA) operator of dimension n is a mapping F: $R^n \longrightarrow R$ with associated weight vector $W = (w_1, w_2, \ldots, w_n)$ and $\sum_{i=1}^{n} w_i = 1$, $w_i \in [0, 1]$ as follows:

$$WWA(a_1, a_2, \ldots, a_n) = \sum_{i=1}^{n} w_i a_i, \tag{9}$$

where a_i is the argument variable.

According to the results of Table 1, equation (9) was used to calculate the bidder scores for software supplier selection, as shown in Table 2.

4.1.2. Solution by the DEA Method. Yang et al. [2] proposed a DEA model with single input and multiple outputs to solve the best-value contractor selection problem. They used the decision-making unit (DMU) as a bidder, and the DEA input values were equal to 1. According to Table 1, the DEAP software was used to run the DEA CCR model, and the software supplier evaluation results as listed in Table 3, where a bidder's DEA value of 100% indicates that the bidder has the highest comparative efficiency.

4.1.3. Solution by the Proposed Novel Contractor Selection Approach. The proposed novel contractor selection approach integrates the PROMETHEE II method and the soft set approach to select suitable contractors. In the software supplier selection example, the five assessment criteria scores for six bidders in the final bid opening committee are as listed in Table 1 (Steps 1 ~ 4). The following procedure describes the remaining steps of the proposed method:

Step 5: normalize the decision matrix.

According to Table 1, equations (1) and (2) were used to calculate the normalized decision matrix for different software suppliers, as listed in Table 4.

Step 6: compute the preference function $P_j(a, b)$.

Step 7: compute the aggregated preference function $\pi(a, b)$.

According to Table 4, equations (3)–(5) were used to compute the preference function ($P_j(a, b)$) and aggregated preference function ($\pi(a, b)$) for different software suppliers, as listed in Table 5.

Step 8: compute the entering flow and leaving flow for each alternative.

According to Table 5, equations (6) and (7) were used to calculate the entering and leaving flows for different software suppliers, as shown in Table 6.

Table 1: Actual evaluation data of software supplier.

Bidder	Criteria				
	C1	C2	C3	C4	C5
Bidder 1	6.2	23.8	23.1	15.6	7.2
Bidder 2	6.0	23.0	23.0	15.0	6.3
Bidder 3	8.0	26.3	26.3	17.5	8.5
Bidder 4	6.7	21.5	22.3	14.8	6.0
Bidder 5	8.8	26.0	27.0	17.0	8.5
Bidder 6	8.2	24.5	26.3	16.7	8.0

Table 2: Software supplier selection by the traditional weighted arithmetic averaging method.

Bidder	Criteria					Total score	Actual winner
	C1	C2	C3	C4	C5		
Bidder 1	6.2	23.8	23.1	15.6	7.2	75.9	
Bidder 2	6.0	23.0	23.0	15.0	6.3	73.3	
Bidder 3	8.0	26.3	26.3	17.5	8.5	87.6	Yes
Bidder 4	6.7	21.5	22.3	14.8	6.0	71.3	
Bidder 5	8.8	26.0	27.0	17.0	8.5	87.0	
Bidder 6	8.2	24.5	26.3	16.7	8.0	84.7	

Step 9: determine the ranking of all possible alternatives.

According to Table 6, equation (8) was used to calculate the net flow for different software suppliers. The net flow values $\varphi(a)$ was ranked from highest to lowest, with a higher net flow value $\varphi(a)$ representing a better software supplier, as listed in Table 7.

4.1.4. Summary. Case Project 1 involves selecting a software supplier to develop a management information system for the case company. The input data for each bidder was listed in Table 1. Table 8 lists the different calculation results of the traditional weighted arithmetic averaging method, the DEA method, and the proposed method for Case Project 1.

From Table 8, the DEA values for bidders 3 and 5 were 100%. The proposed extended PROMETHEE II method can solve this problem of duplicate DEA value. In the proposed method, the net outranking flow of bidders 3 and 5 were 0.490 and 0.511, respectively. Therefore, the proposed method can better sort bidder scores.

4.2. Case Project 2. Case Project 2 involves the selection of two security companies to provide security services for a science park [2]. There were seven bidders competing for two awards in this case. The assessment criteria included company organization (C1), planning feasibility (C2), professional capability (C3), price (C4), and presentation and question response (C5). The relative weights for the five assessment criteria were 0.20, 0.25, 0.25, 0.20, and 0.10, respectively, and the final evaluation committee selected the best two security services companies based on the five assessment criteria. The five assessment criteria scores for each security services company are listed in Table 9.

4.2.1. Solution by the Traditional Weighted Arithmetic Average Approach. Based on the results of Table 9, equation (9) was used to calculate the bidder scores for security services company selection, as shown in Table 10.

4.2.2. Solution by the DEA Method. According to the data in Table 9, the DEAP software was used to run the DEA CCR model. The security services company selection evaluation results are listed in Table 11. In Table 11, a bidder's DEA value of 100% indicates that the bidder's performance is the highest.

4.2.3. Solution by the Proposed Method. According to the results of Table 9, equations (1) and (2) were used to calculate the normalized decision matrix of different security companies, as listed in Table 12.

According to the results of Table 12, equations (3)–(5) were used to calculate the preference function $P_j(a,b)$ and aggregated preference function for different security companies, as shown in Table 13.

According to the results of Table 13, equations (6)–(8) were used to calculate the entering flow, leaving flow, and net outranking flow for different security companies, as listed in Table 14.

4.2.4. Summary. Case Project 2 involved the selection of two security companies to provide security for a science park in Taiwan. Table 15 displays the calculation results of the traditional weighted arithmetic averaging method, the DEA method, and the proposed method for Case Project 2.

In Table 15, the traditional weighted arithmetic averaging method identifies bidders 1 and 6 as having the two highest scores, thus the winning bidders. However, the traditional weighted arithmetic averaging method does not consider the relative importance of the criteria or subjective preferences of the experts, which will result in an incorrect conclusion. From Table 15, the DEA values for bidders 1, 2, 3, 6, and 7 are 100%. The DEA method thus has a high duplicate rate problem. The proposed extended PROMETHEE II method simultaneously considers the objective weights of the assessment criteria and the subjective preferences of the experts. Thus, the proposed method identifies the top two net outranking flows as 0.279 (bidder 1) and 0.212 (bidder 2), which are the winning bids. Therefore, the proposed extended PROMETHEE II approach is more suitable for solving the contractor selection problem.

4.3. Case Project 3. Case Project 3 involved the selection of the best contractor for a local Koji pottery industry promotion company in Chiayi, Taiwan [42]. In this local Koji pottery industry promotion case, there were three bidders, and the final evaluation committee consisted of four committee members. The assessment criteria included the content of service proposal (C1), service management and control of the project (C2), bidder's bid price and components (C3), project ideas and feedback (C4), and brief and responsive (C5). The relative weights for the five assessment

Table 3: Software supplier DEA evaluation results.

DMU	Output 1	Output 2	Output 3	Output 4	Output 5	Input	DEA value (%)	Actual winner
DMU 1	6.2	23.8	23.1	15.6	7.2	1.0	90.5	
DMU 2	6.0	23.0	23.0	15.0	6.3	1.0	87.5	
DMU 3	8.0	26.3	26.3	17.5	8.5	1.0	100.0	Yes
DMU 4	6.7	21.5	22.3	14.8	6.0	1.0	84.7	
DMU 6	8.8	26.0	27.0	17.0	8.5	1.0	100.0	Yes
DMU 6	8.2	24.5	26.3	16.7	8.0	1.0	97.8	

Table 4: Normalized the decision matrix for different software suppliers.

Bidder	Criteria				
	C1	C2	C3	C4	C5
Bidder 1	0.071	0.479	0.170	0.296	0.480
Bidder 2	0.000	0.313	0.149	0.074	0.120
Bidder 3	0.714	1.000	0.851	1.000	1.000
Bidder 4	0.250	0.000	0.000	0.000	0.000
Bidder 5	1.000	0.938	1.000	0.815	1.000
Bidder 6	0.786	0.625	0.851	0.704	0.800

Table 5: Aggregated preference function for different software suppliers.

Bidder	Bidder 1	Bidder 2	Bidder 3	Bidder 4	Bidder 5	Bidder 6
Bidder 1	—	0.144	0.000	0.302	0.000	0.000
Bidder 2	0.000	—	0.000	0.165	0.000	0.000
Bidder 3	0.618	0.762	—	0.902	0.056	0.192
Bidder 4	0.018	0.025	0.000	—	0.000	0.000
Bidder 5	0.635	0.779	0.073	0.919	—	0.202
Bidder 6	0.433	0.577	0.007	0.717	0.000	—

Table 6: Entering and leaving flows for different software suppliers.

Bidder	Entering flow	Leaving flow
Bidder 1	0.341	0.089
Bidder 2	0.457	0.033
Bidder 3	0.016	0.506
Bidder 4	0.601	0.009
Bidder 5	0.011	0.522
Bidder 6	0.079	0.347

Table 7: Net outranking flow values for different alternative software suppliers.

Bidder	Net outranking flow	Rank
Bidder 1	−0.251	4
Bidder 2	−0.424	5
Bidder 3	0.490	2
Bidder 4	−0.593	6
Bidder 5	0.511	1
Bidder 6	0.268	3

criteria were 0.30, 0.25, 0.15, 0.20, and 0.10, respectively. Performance evaluation scores of each bidder are listed in Table 16.

4.3.1. Solution by the Traditional Weighted Arithmetic Average Approach. Some information provided by Expert P3 were missing or nonexistent data, and thus, only information provided by Experts P1, P2, and P4 were considered. According to the results of Table 16, equation (9) was used to calculate the bidder scores for local Koji pottery industry promotion contractor selection, as shown in Table 17.

4.3.2. Solution by the DEA Method. From Table 16, Experts P1, P2, and P4 provided complete evaluation information, while Expert P3's evaluation information was incomplete. The DEA method can only work with complete expert information. Therefore, only the information provided by Experts P1, P2, and P4 were considered. According to Table 16, the DEAP software was used to run the DEA CCR model, and the local Koji pottery industry promotion company selection evaluation result is shown in Table 18.

4.3.3. Solution by the Proposed Method. The proposed novel contractor selection technique is not only able to handle the objective weights of assessment criteria and subjective preferences of experts but can also handle missing or nonexistent contractor selection assessment process data by using the average value of the complete information to complete the information. According to Table 16, equations (1) and (2) were used to compute normalized decision matrix for the local Koji pottery industry promotion companies, as listed in Table 19.

According to Table 19, quations (3)–(5) were used to calculate the preference function $P_j(a,b)$ and aggregated preference function for different local Koji pottery industry promotion companies, as shown in Table 20.

According to Table 20, equations (6)–(8) were used to calculate the entering flow, leaving flow, and net outranking flow of different local Koji pottery industry promotion companies, as shown in Table 21.

4.3.4. Summary. Case Project 3 involved the selection of the best bidder as a local Koji pottery industry promotion company in Taiwan. Table 22 shows the calculation results of the traditional weighted arithmetic averaging method, the DEA method, and the proposed method for Case Project 3.

Table 8: Results of different calculation methods for Case Project 1.

Bidder	Traditional weighted arithmetic averaging method		DEA method		The proposed method	
	Total score	Ranking	DEA value (%)	Ranking	Net outranking flow	Ranking
Bidder 1	75.9	4	90.5	4	−0.251	4
Bidder 2	73.3	5	87.5	5	−0.424	5
Bidder 3	87.6	1	100.0	1	0.490	2
Bidder 4	71.3	6	84.7	6	−0.593	6
Bidder 5	87.0	2	100.0	1	0.511	1
Bidder 6	84.7	3	97.8	3	0.268	3

Table 9: Actual evaluation data of security services companies.

Bidder	Criteria				
	C1	C2	C3	C4	C5
Bidder 1	18.0	20.5	20.2	17.5	7.8
Bidder 2	13.0	22.0	21.0	17.0	8.0
Bidder 3	18.3	19.7	18.8	16.8	7.8
Bidder 4	12.5	18.5	17.3	17.2	7.2
Bidder 5	12.7	21.3	20.1	16.1	7.7
Bidder 6	17.4	20.1	19.1	17.0	8.0
Bidder 7	16.9	19.9	18.9	17.0	8.0

Table 10: Security services company selection by the traditional weighted arithmetic average approach.

Bidder	Criteria					Total score	Actual winner
	C1	C2	C3	C4	C5		
Bidder 1	18.0	20.5	20.2	17.5	7.8	84.0	Yes
Bidder 2	13.0	22.0	21.0	17.0	8.0	81.0	
Bidder 3	18.3	19.7	18.8	16.8	7.8	81.5	
Bidder 4	12.5	18.5	17.3	17.2	7.2	72.7	
Bidder 5	12.7	21.3	20.1	16.1	7.7	78.0	
Bidder 6	17.4	20.1	19.1	17.0	8.0	81.7	Yes
Bidder 7	16.9	19.9	18.9	17.0	8.0	80.6	

Table 11: Security services company DEA evaluation results.

DMU	Output 1	Output 2	Output 3	Output 4	Output 5	Input	DEA value (%)	Actual winner
DMU 1	18.0	20.5	20.2	17.5	7.8	1.0	100.0	Yes
DMU 2	13.0	22.0	21.0	17.0	8.0	1.0	100.0	Yes
DMU 3	18.3	19.7	18.8	16.8	7.8	1.0	100.0	Yes
DMU 4	12.5	18.5	17.3	17.2	7.2	1.0	98.3	
DMU 5	12.7	21.3	20.1	16.1	7.7	1.0	96.9	
DMU 6	17.4	20.1	19.1	17.0	8.0	1.0	100.0	Yes
DMU 7	16.9	19.9	18.9	17.0	8.0	1.0	100.0	Yes

Table 12: Normalized the decision matrix of different security companies.

Bidder	Criteria				
	C1	C2	C3	C4	C5
Bidder 1	0.948	0.571	0.784	1.000	0.750
Bidder 2	0.086	1.000	1.000	0.643	1.000
Bidder 3	1.000	0.343	0.405	0.500	0.750
Bidder 4	0.000	0.000	0.000	0.786	0.000
Bidder 5	0.034	0.800	0.757	0.000	0.625
Bidder 6	0.845	0.457	0.486	0.643	1.000
Bidder 7	0.759	0.400	0.432	0.643	1.000

Table 13: Aggregated preference function of different security companies.

Bidder	Bidder 1	Bidder 2	Bidder 3	Bidder 4	Bidder 5	Bidder 6	Bidder 7
Bidder 1	—	0.244	0.252	0.646	0.402	0.195	0.240
Bidder 2	0.186	—	0.367	0.617	0.287	0.264	0.292
Bidder 3	0.010	0.183	—	0.462	0.306	0.031	0.048
Bidder 4	0.000	0.029	0.057	—	0.157	0.029	0.029
Bidder 5	0.057	0.000	0.202	0.459	—	0.153	0.181
Bidder 6	0.025	0.152	0.102	0.505	0.328	—	0.045
Bidder 7	0.025	0.134	0.075	0.460	0.311	0.000	—

Table 14: Entering, leaving, and net flows for different security companies.

Bidder	Entering flow	Leaving flow	Net outranking flow
Bidder 1	0.051	0.330	0.279
Bidder 2	0.124	0.336	0.212
Bidder 3	0.176	0.173	−0.002
Bidder 4	0.525	0.050	−0.475
Bidder 5	0.299	0.175	−0.123
Bidder 6	0.112	0.193	0.081
Bidder 7	0.139	0.167	0.028

Table 15: Results of different calculation methods for Case Project 2.

Bidder	Traditional weighted arithmetic averaging method		DEA method		The proposed method	
	Total score	Ranking	DEA value (%)	Ranking	Net outranking flow	Ranking
Bidder 1	84.0	1	100.0	1	0.279	1
Bidder 2	81.0	4	100.0	1	0.212	2
Bidder 3	81.5	3	100.0	1	−0.002	5
Bidder 4	72.7	7	98.3	6	−0.475	7
Bidder 5	78.0	6	96.9	7	−0.123	6
Bidder 6	81.7	2	100.0	1	0.081	3
Bidder 7	80.6	5	100.0	1	0.028	4

Table 16: Performance evaluation scores of local Koji pottery industry promotion contractors.

Criterion	Weighting (%)	Expert	Bidder 1	Bidder 2	Bidder 3
C1	30	P1	25	24	25
		P2	24	25	25
		P3	24	23	24
		P4	24	25	24
C2	25	P1	23	23	22
		P2	22	22	21
		P3	*	*	*
		P4	21	20	21
C3	15	P1	11	13	12
		P2	11	12	12
		P3	12	13	12
		P4	12	13	12
C4	20	P1	17	18	17
		P2	16	16	17
		P3	15	16	18
		P4	15	17	17
C5	10	P1	8	7	8
		P2	6	6	7
		P3	7	7	8
		P4	8	7	7

*indicates missing or nonexistent data.

Table 17: Local Koji pottery industry promotion contractor selection by the traditional weighted arithmetic averaging method.

Bidder	Expert	Criteria C1	C2	C3	C4	C5	Total score	Actual winner
Bidder 1	P1	25	23	11	17	8	81.0	
	P2	24	22	11	16	6		
	P4	24	21	12	15	8		
Bidder 2	P1	24	23	13	18	7	82.7	Yes
	P2	25	22	12	16	6		
	P4	25	20	13	17	7		
Bidder 3	P1	25	22	12	17	8	82.3	
	P2	25	21	12	17	7		
	P4	24	21	12	17	7		

Table 18: DEA local Koji pottery industry promotion contractor evaluation result.

Bidder	Output 1	Output 2	Output 3	Output 4	Output 5	Input	DEA value (%)	Actual winner
Bidder 1	24.3	22.0	11.3	16.0	7.3	1.0	100.0	Yes
Bidder 2	24.7	21.7	12.7	17.0	6.7	1.0	100.0	Yes
Bidder 3	24.7	21.3	12.0	17.0	7.3	1.0	100.0	Yes

Table 19: Normalized the decision matrix for different promotion contractors.

Bidder	Criteria C1	C2	C3	C4	C5
Bidder 1	0.000	1.000	0.000	0.000	0.667
Bidder 2	0.000	0.500	1.000	0.667	0.000
Bidder 3	1.000	0.000	0.400	1.000	1.000

Table 20: Aggregated preference function for different promotion contractors.

Bidder	Bidder 1	Bidder 2	Bidder 3
Bidder 1	—	0.192	0.250
Bidder 2	0.283	—	0.215
Bidder 3	0.593	0.467	—

Table 21: Entering, leaving, and net flows of different promotion contractors.

Bidder	Entering flow	Leaving flow	Net outranking flow
Bidder 1	0.438	0.221	−0.218
Bidder 2	0.329	0.249	−0.080
Bidder 3	0.233	0.530	0.298

Table 22: Results of different calculation methods for Case Project 3.

Bidder	Traditional weighted arithmetic averaging method		DEA method		The proposed method	
	Total score	Ranking	DEA value (%)	Ranking	Net outranking flow	Ranking
Bidder 1	81.0	3	100.0	1	−0.218	3
Bidder 2	82.7	1	100.0	1	−0.080	2
Bidder 3	82.3	2	100.0	1	0.298	1

From Table 22, the DEA values of bidders 1, 2, and 3 are 100%, which illustrates the high repetition rate problem of the DEA method. Moreover, neither the traditional weighted arithmetic averaging method nor the DEA method can handle incomplete contractor selection process information. Therefore, the proposed method is more a general contractor selection technique and better suited for handling real-world problems.

5. Conclusions

Contractor selection is a critical component of any company's pursuit of sustainable development, in addition, choosing suitable contractors ensures that project management plans are executed as expected. However, contractor selection includes qualitative and quantitative assessment criteria at the same time, which becomes a complicated MCDM problem. Traditional contractor selection methods are unable to handle nonexistent or missing assessment criteria data nor consider the relative importance of criteria in the contractor selection assessment process. In order to effectively address this problem, this study extended the PROMETHEE II method to propose a novel contractor selection technique. Moreover, three numerical examples are applied to prove the correctness and effectiveness of the proposed technique. The simulation results showed that the proposed extended PROMETHEE II approach is a more general contractor selection technique for handling incomplete information than the traditional weighted arithmetic averaging method and the DEA method.

The main advantages of the proposed extended PROMETHEE II approach are as follows:

(1) The proposed approach can handle incomplete assessment criteria information

(2) The proposed approach considers the relative importance of criteria

(3) The proposed approach considers the subjective preferences of experts

(4) The traditional weighted arithmetic average approach and DEA method can be viewed as special cases of the proposed approach

(5) The proposed approach provides a more flexible contractor selection technique to support contractor assessment for selection

This paper assumed that the experts have the same weight and did not consider the objective weight of the evaluation data. Further research studies can explore the simultaneous considerations of subjective and objective weights of assessment criteria to handle different field decision-making issues.

Data Availability

The contractor selection data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares that there are no conflicts of interest.

Acknowledgments

The authors would like to thank the Ministry of Science and Technology, Taiwan, for financially supporting this research under Contract Nos. MOST 109-2410-H-145-002 and MOST 110-2410-H-145-001.

References

[1] J. R. San Cristóbal, "Contractor selection using multicriteria decision-making methods," *Journal of Construction Engineering and Management*, vol. 138, no. 6, pp. 751–758, 2012.

[2] J. B. Yang, H. H. Wang, W. C. Wang, and S. M. Ma, "Using data envelopment analysis to support best-value contractor selection," *Journal of Civil Engineering and Management*, vol. 22, no. 2, pp. 199–209, 2015.

[3] C. Akcay, E. Manisali, and E. Manisalı, "Fuzzy decision support model for the selection of contractor in construction works," *Revista de la construcción*, vol. 17, no. 2, pp. 258–266, 2018.

[4] M. Hasnain, M. J. Thaheem, and F. Ullah, "Best value contractor selection in road construction projects: ANP-based decision support system," *International Journal of Civil Engineering*, vol. 16, no. 6A, pp. 695–714, 2018.

[5] K. H. Chang, "A novel supplier selection method that integrates the intuitionistic fuzzy weighted averaging method and a soft set with imprecise data," *Annals of Operations Research*, vol. 272, no. 1-2, pp. 139–157, 2019.

[6] G. Gharedaghi and M. Omidvari, "A pattern of contractor selection for oil and gas industries in a safety approach using ANP-DEMATEL in a Grey environment," *International Journal of Occupational Safety and Ergonomics*, vol. 25, no. 4, pp. 510–523, 2019.

[7] D. Molodtsov, "Soft set theory—first results," *Computers & Mathematics with Applications*, vol. 37, no. 4-5, pp. 19–31, 1999.

[8] S. Danjuma, T. Herawan, M. A. Ismail, H. Chiroma, A. I. Abubakar, and A. M. Zeki, "A review on soft set-based parameter reduction and decision making," *IEEE Access*, vol. 5, pp. 4671–4689, 2017.

[9] K.-H. Chang, "A more general risk assessment methodology using a soft set-based ranking technique," *Soft Computing*, vol. 18, no. 1, pp. 169–183, 2014.

[10] B. Biswas, S. Bhattacharyya, A. Chakrabarti, K. N. Dey, J. Platos, and V. Snasel, "Colonoscopy contrast-enhanced by intuitionistic fuzzy soft sets for polyp cancer localization," *Applied Soft Computing*, vol. 95, Article ID 106492, 2020.

[11] K.-H. Chang, "A novel reliability allocation approach using the OWA tree and soft set," *Annals of Operations Research*, vol. 244, no. 1, pp. 3–22, 2016.

[12] Z. Tao, H. Chen, L. Zhou, and J. Liu, "2-Tuple linguistic soft set and its application to group decision making," *Soft Computing*, vol. 19, no. 5, pp. 1201–1213, 2015.

[13] F. Hao, Z. Pei, D.-S. Park, V. Phonexay, and H.-S. Seo, "Mobile cloud services recommendation: a soft set-based approach," *Journal of Ambient Intelligence and Humanized Computing*, vol. 9, no. 4, pp. 1235–1243, 2018.

[14] B. Paik and S. K. Mondal, "A distance-similarity method to solve fuzzy sets and fuzzy soft sets based decision-making problems," *Soft Computing*, vol. 24, no. 7, pp. 5217–5229, 2020.

[15] M. Abbas, M. Ali, and S. Romaguera, "Generalized operations in soft set theory via relaxed conditions on parameters," *Filomat*, vol. 31, no. 19, pp. 5955–5964, 2017.

[16] K.-H. Chang, "Enhanced assessment of a supplier selection problem by integration of soft sets and hesitant fuzzy linguistic term set," *Proceedings of the Institution of Mechanical*

Engineers—Part B: Journal of Engineering Manufacture, vol. 229, no. 9, pp. 1635–1644, 2015.
[17] Z. Kong, J. Zhao, L. Wang, and J. Zhang, “A new data filling approach based on probability analysis in incomplete soft sets,” *Expert Systems with Applications*, vol. 184, Article ID 115358, 2021.
[18] M. Akram, M. Shabir, A. Adeel, and A. N. Al-Kenani, “A multiattribute decision-making framework: VIKOR method with complex spherical fuzzy N-soft sets,” *Mathematical Problems in Engineering*, vol. 2021, Article ID 1490807, 2021.
[19] T. C. Wen, K. H. Chang, and H. H. Lai, “Integrating the 2-tuple linguistic representation and soft set to solve supplier selection problems with incomplete information,” *Engineering Applications of Artificial Intelligence*, vol. 87, Article ID 103248, 2020.
[20] O. Dalkilic, “A novel approach to soft set theory in decision-making under uncertainty,” *International Journal of Computer Mathematics*, vol. 98, no. 10, pp. 11935–11945, 2021.
[21] J. P. Brans and P. Vincke, “Note-A preference ranking organisation method,” *Management Science*, vol. 31, no. 6, pp. 647–656, 1985.
[22] J. M. Brankovic, M. Markovic, and D. Nikolic, “Comparative study of hydraulic structures alternatives using promethee II complete ranking method,” *Water Resources Management*, vol. 32, no. 10, pp. 3457–3471, 2018.
[23] X. J. Tian, X. D. Liu, and L. D. Wang, “An improved PROMETHEE II method based on axiomatic fuzzy sets,” *Neural Computing and Applications*, vol. 25, no. 7-8, pp. 1675–1683, 2014.
[24] F. Samanlioglu and Z. Ayağ, “A fuzzy AHP-PROMETHEE II approach for evaluation of solar power plant location alternatives in Turkey,” *Journal of Intelligent & Fuzzy Systems*, vol. 33, no. 2, pp. 859–871, 2017.
[25] M. Rabbani, R. Heidari, and H. Farrokhi-Asl, “A bi-objective mixed-model assembly line sequencing problem considering customer satisfaction and customer buying behaviour,” *Engineering Optimization*, vol. 50, no. 12, pp. 2123–2142, 2018.
[26] D. Jovanovic and D. Cvetkovic, “Multiple decision making criteria in the implementation of renewable energy sources,” *Tehnicki Vjesnik-Technical Gazette*, vol. 25, no. 5, pp. 1492–1496, 2018.
[27] W. Zhang, C. Wang, L. Zhang et al., “Evaluation of the performance of distributed and centralized biomass technologies in rural China,” *Renewable Energy*, vol. 125, pp. 445–455, 2018.
[28] D. F. D. Silva, J. C. S. Silva, L. G. O. Silva, L. Ferreira, and A. T. de Almeida, “Sovereign credit risk assessment with multiple criteria using an outranking method,” *Mathematical Problems in Engineering*, vol. 2018, Article ID 8564764, 11 pages, 2018.
[29] A. d. S. Barbosa, R. A. Shayani, and M. A. G. d. Oliveira, “A multi-criteria decision analysis method for regulatory evaluation of electricity distribution service quality,” *Utilities Policy*, vol. 53, pp. 38–48, 2018.
[30] G. Markovic, N. Zdravkovic, M. Karakasic, and M. Kolarevic, “Modified PROMETHEE approach for solving multi-criteria location problems with complex criteria functions,” *Tehnicki Vjesnik-Technical Gazette*, vol. 27, no. 1, pp. 12–19, 2020.
[31] L. Z. Tong, Z. M. Pu, K. Chen, and J. J. Yi, “Sustainable maintenance supplier performance evaluation based on an extend fuzzy PROMETHEE II approach in petrochemical industry,” *Journal of Cleaner Production*, vol. 273, Article ID 122771, 2020.
[32] R. Liu, Y. J. Zhu, Y. Chen, and H. C. Liu, “Occupational health and safety risk assessment using an integrated TODIM-PROMETHEE model under linguistic spherical fuzzy environment,” *International Journal of Intelligent Systems*, vol. 36, no. 11, pp. 6814–6836, 2021.
[33] W. Torbacki, “A hybrid MCDM model combining DANP and PROMETHEE II methods for the assessment of cybersecurity in industry 4.0,” *Sustainability*, vol. 13, no. 16, p. 8833, 2021.
[34] M. S. Roodposhti, S. Rahimi, and M. J. Beglou, “PROMETHEE II and fuzzy AHP: an enhanced GIS-based landslide susceptibility mapping,” *Natural Hazards*, vol. 73, no. 1, pp. 77–95, 2014.
[35] A. Kessili and S. Benmamar, “Prioritizing sewer rehabilitation projects using AHP-PROMETHEE II ranking method,” *Water Science and Technology*, vol. 73, no. 2, pp. 283–291, 2016.
[36] S. R. Maity and S. Chakraborty, “Tool steel material selection using PROMETHEE II method,” *International Journal of Advanced Manufacturing Technology*, vol. 78, no. 9-12, pp. 1537–1547, 2015.
[37] M. I. Ali, M. Shabir, and F. Feng, “Representation of graphs based on neighborhoods and soft sets,” *International Journal of Machine Learning and Cybernetics*, vol. 8, no. 5, pp. 1525–1535, 2017.
[38] P. K. Maji, R. Biswas, and A. R. Roy, “Soft set theory,” *Computers and Mathematics with Applications*, vol. 45, no. 4-5, pp. 555–562, 2003.
[39] K. H. Chang, Y. C. Chang, K. Chain, and H. Y. Chung, “Integrating soft set theory and fuzzy linguistic model to evaluate the performance of training simulation systems,” *PLoS One*, vol. 11, no. 9, Article ID e0162092, 2016.
[40] Z. Xu, “A note on linguistic hybrid arithmetic averaging operator in multiple attribute group decision making with linguistic information,” *Group Decision and Negotiation*, vol. 15, no. 6, pp. 593–604, 2006.
[41] J. M. Merigó, “A unified model between the weighted average and the induced OWA operator,” *Expert Systems with Applications*, vol. 38, no. 9, pp. 11560–11572, 2011.
[42] K. H. Chang, “A general soft set and the OWA approach for a supplier selection problem under incomplete information,” *ICIC Express Letters, Part B: Applications*, vol. 4, no. 2, pp. 395–400, 2013.

Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 4130972, 14 pages
https://doi.org/10.1155/2021/4130972

Research Article

In a Stressful Social Environment, Can Using Sports Apps Relieve the Physical and Mental Stress of the Elderly? From the Perspective of Industry 4.0

Po-Fang Huan,[1] Chih-Yen Chen,[2] Hsiao-Hsien Lin,[3] I-Chi Wang,[4] and Chin-Hsien Hsu[3]

[1]*Physical Office of Fu Jen Catholic University, New Taipei, Taiwan*
[2]*General Education Center, National Taitung Junior College, Taitung, Taiwan*
[3]*School of Physical Education, Jiaying University, Meizhou City, Guangdong Province, China*
[4]*Department of Industrial Education and Technology, National Changhua University of Education, Changhua, Taiwan*

Correspondence should be addressed to Chin-Hsien Hsu; hsu6292000@yahoo.com.tw

Received 1 July 2021; Accepted 22 September 2021; Published 12 November 2021

Academic Editor: Kim-Hua Tan

The purpose of this research was to understand the current physical and mental health of the elderly using sports apps under the COVID-19 pandemic. A total of 711 questionnaires were collected using purposive sampling and the snowball method and were analyzed by Statistical Product and Service Solutions 22.0 and Analysis of Moment Structures 20.0 software. The survey found that elderly people who exercise at intervals of one month are more physically and mentally stressed, but that different exercise frequencies also have different levels of physical and mental health problems; the lower the exercise intensity, the more obvious the negative emotions, the stronger or the less time they spend in exercise, and the greater the pressure of sports. In a high-risk social environment, even if the elderly use sports apps to exercise, they will still change the intensity and time of the exercise, but they will not change the frequency of exercise that has become a daily habit.

1. Introduction

The COVID-19 pandemic is no longer a single health problem but rather a national and human crisis, as well as a major public security incident [1–3]. There have been cases of infectious diseases in the past, such as SARS and MERS, yet SARS, MERS, and COVID-19 are all the same type of virus with regular intervals of occurrence, and all three viruses are capable of endangering human health and causing serious damage to industrial development. Since the discovery of COVID-19 cases on December 26, 2019, the epidemic has spread rapidly, infecting large numbers of people. According to the statistics on May 4, 2020, a total of 187 countries were facing the impact of the epidemic, and the number of confirmed cases reached almost 23.7 million with 814,000 deaths in 127 days [4]. Patients mainly present with alveolar damage, decreased oxygenation of the blood, decreased organ function due to inadequate oxygen supply [5], and eventually respiratory failure leading to death, with a mortality rate of 5.95% [6]. The current research found that COVID-19 has a clear mode of transmission, a long survival period of the virus in the air, the inability to distinguish the carrier by the symptoms [6], damage to the immune system [7–9], and an uncertain mode of transmission. It has hampered global economic development [1–3] and put individuals and communities under tremendous pressure, anxiety, and trauma [10]. It is obvious that COVID-19 is no longer an isolated health problem but has become a major national and human crisis as well as a public safety and health incident [1, 3, 11, 12]. It has been eight months since the COVID-19 pandemic began, and there is still no sign of a solution. During this period of time, the pressure of the epidemic has impacted human beings all over the world and caused the shock of physical and psychological stress. It has been found that people who have been exposed to COVID-19 or have made a prior visit to an infected country and had to undergo self-quarantine and testing with inadequate supplies and information often suffer from fear, depression, boredom [13], and stress, leading to an increase in suicide and homicidal suicide rates [14, 15] and seriously affecting individuals' physical and mental health [15]. The lack of familiarity with technical software or the infrequent use of Internet technology for information exchange can cause the elderly to suffer higher mortality rates than other age groups under the pressure of this COVID-19 pandemic [16]. In addition to the immediate impact, postdisaster trauma can arise from these problems [17]. The human individual is the main object of community and society cohesion as well as the key to industrial and economic circulation. The experience of the impact of the global viral influenza (COVID-19) epidemic has shown that humans cannot respond quickly to rapid virus transitions [6, 9, 17, 18] and that it is not possible to predict whether novel viruses with unique genes will emerge again, so we can only formulate policies to prevent and improve the situation [19].

COVID-19 is a global epidemic, and the current epidemic prevention policy is to prevent people who are not yet affected by the virus or who are in areas that are already contaminated by the virus from being infected. When people are infected with the virus, their physical and mental health will be affected [14, 16, 17], causing a series of economic, social, and environmental impacts on individuals, societies, and nations [1–3]. Therefore, it is crucial to maintain good health, improve human behavior, increase mobility, enhance immunity [20], reduce stress, prevent health and psychological diseases [20], overcome anxiety and reduce depression [21], minimize the risk of disease [22], improve individuals' psychological status, promote social interaction and sensitivity [21], improve physical and mental health, and act correctly to avoid the impact on the overall economy and development of individuals, society, and country.

Through the accumulation of human wisdom, human beings have used machines and tools to resolve difficulties and satisfy the needs of life and work. In continuation of the Industrial Revolution at the end of the 18th century, mankind created steam power, electric appliances, computers, and other technological advancements. Now in the 21st century, with the emergence of the Internet, alternative energy, novel materials, and biotechnology, human civilization is making a great leap forward again with the application of automation technology, cloud computing, and artificial intelligence to operate machinery for human happiness and stability of life. This is called Industry 4.0.

Industry 4.0 refers to the effective management and analysis of users. It drives production, services, and even business models through the integration of the Internet. It includes the provision of the Internet of things, big data and analytics, additive manufacturing, automation, system integration, cyber security, augmented reality, simulations, and other industries [23]. These areas are all encompassed by the definition of Industry 4.0 and are gradually being extended [24].

Population aging is a global trend, and the number of elderly citizens in most countries is increasing every year. Although technology has brought about advances in human life and medical care that have extended life expectancies, it has also increased the pressure of work and life, and it has gradually deprived people of the opportunity to exercise. The physical functions of the elderly may be reduced due to changes in the environment and internal physiological factors [25], showing that the physical and mental health of the elderly is fragile. In particular, under the environmental pressure of global infectious disease epidemics, the physical and psychological health of the elderly are under greater threat [16].

The sports industry has seized the opportunity and introduced Industry 4.0 technology to develop sports apps that are suitable for the elderly (Table 1), hoping to promote a sports culture and enter the market of sports and health for the elderly using the concepts of exercise at any time and real-time self-monitoring [26]. For consumers, the main purpose of sports apps is to provide users with exercise expertise and technology to improve their health through real-time online technology and computing, together with the concept of customization. However, although exercise can improve physical health, the effectiveness of any improvement can only be seen after a period of participation and experience [27]. From the perspective of long-term users, the most practical and clear answers can be obtained through systematic data compilation, collection, and analysis [28].

Scholars believe that Internet technology can help human exercise [29], and literature on Internet technology intervention in elderly health has shown that health technology apps can assist medical professionals in remotely monitoring the health of the elderly [30] and enhancing the self-health management of the elderly patients at home [31]. However, since prevention is better than treatment [30], in recent years, scholars have gradually begun to focus on the physical and mental health of the elderly [32]. Unfortunately, the research on exercise apps and the elderly has so far been limited to exploring the effectiveness of the software in managing the health of the elderly [29, 30, 31] and the health maintenance and management of the elderly in the community [32]. There is a lack of literature on the physical and mental health of the elderly [33] or the physical and mental health of the elderly after using exercise apps [32, 33]. Therefore, it is suggested that the study of the impact of online exercise apps on the physical and mental health of elderly people can be improved by the introduction of Industry 4.0 technology.

2. Theoretical Framework

2.1. Industry 4.0 Sports Apps for the Elderly. At the beginning of the 21st century, the so-called Industry 4.0 is being realized in the use of the Internet, alternative energy, novel materials, and biotechnology to intervene in the human operation of machinery or equipment. The movement is further utilized on the foundation of artificial intelligence, through perception, human-computer communication, decision-making, implementation and feedback, and procedures to achieve product design, manufacturing process, management, and service intellectualization of the CPPS model. [34], that is, the

Table 1: Questionnaire on the impact of leisure sports behavior and physical and mental health.

Main classification	Content	Numbering
Background information	Gender, education level	1-2
Recreational sports behavior	Leisure exercise intensity, leisure exercise time, leisure exercise frequency	3–5
Physical and mental health impact	C1 cannot cope with things around C2 is easy to feel scared C3 is not satisfied with his work performance C4 is not interested in things or activities C5 cannot make full use of time	6–10
	D1 feels headache or head pressure D2 feels tired or exhausted, exhausted D3 felt pain in a certain part of the body and thought I was sick D4 feeling of back pain D5 insomnia or poor sleep	11–15
	E1 stomach pain, indigestion E2 increases diet and smoking E3 feels stiff and tight	16–18
	F1 becomes impatient and loses temper easily F2 considers itself worthless F3 feels that work and life are meaningless F4 wants to use self-harm to escape everything	19–22

realization of Industry 4.0 [24]. Thus, for consumers, the main purpose of sports apps is to provide users with exercise expertise and technology to improve their health through real-time online technology and computing and the concept of customization. However, although exercise can improve physical health, the effectiveness of such improvement can only be seen after a period of participation and experience [27, 30]. From the perspective of long-term users, the most practical and clear answers can be obtained through systematic data compilation, collection, and analysis [28].

The cloud intelligence technology intervention industry is a technical concept of a borderless network. Adopting artificial intelligence to develop exercise prescription or exercise management systems that help people engage in various leisure sports is a trend [33] that meets the current lifestyle and health needs of general and senior citizens. Exercise app software is expected to bring users effective health management measures, so as to gain the trust of consumers to continue using and create business opportunities. The ultimate goal of each product or decision is to know the real outcome of the user, especially the person directly involved [27, 28]. However, although the development of exercise app software has been discussed by some scholars, researchers have found that the current status of research on exercise apps for the elderly is mainly to understand how to monitor and manage the health of the elderly [29, 30, 32] or analyze the users' feelings toward the products [35–37]. There are few studies on changes in the physical and mental health of the elderly after using exercise apps. Therefore, based on the above analysis results, the researchers believed that it would be beneficial to explore the physical and mental health of the elderly after using sports applications.

2.2. Theoretical Framework for the Effects of Recreational Sports Behavior on Physical and Mental Health. With sufficient scientific evidence, effective, rational, and correct decision-making can be achieved [37]. To investigate the relationship between recreational sports behavior and physical and mental health, it is necessary to start with recreational sports behavior. Recreational sports behavior can be explored in terms of recreational frequency, recreational time, and recreational intensity [38]. Good recreational sports behavior can maintain health, and regular exercise habits in daily life can achieve the effect of maintaining health [39]. Studies have shown that exercise can promote awareness of physical and mental health maintenance, improve diet and lifestyle habits [39], increase immunity [20], reduce the risk of viral infection [20], adjust psychological stress [20, 21], and avoid potentially infectious environments [37, 39]. Thus, there is both a direct and indirect influence of recreational sports behavior on physical and mental health.

However, it is also important to understand whether or not recreational sports behavior has an impact on physical and mental health. In order to understand the key factors of physical and mental health, it is necessary to start by understanding the connotation and definition of physical and mental health. The WHO states that physical and mental health refers to the state of good health in both the physical and psychological aspects of an individual [40]. Based on this, research scales related to physical and mental health have been developed to investigate the effects of exercise behavior and self-efficacy [41, 42]. The original scales had too many questions, but gradually the research survey areas have been further categorized, and the questions of the scale have been gradually improved and refined. The Kessler Psychological Distress Scale was introduced in 2014. It has only 10 questions and mainly focuses on the respondents' psychological stress problems over a one-month period [43]. The main content of the survey asks about feelings of tiredness, tension, inability to calm down, despair, irritability, restlessness, frustration, sense of accomplishment, sadness, and worthlessness [44]. Without compromising the privacy of the participants, the survey provides valid information about the mental health status of the participants under the concept of self-assessment in order to raise the awareness of people's depression and anxiety and to construct preventive measures [43].

Health is not only about psychological and physiological aspects but is also a manifestation of the physical state and immunity [40]. According to the literature, Cheng and Williams designed the CHQ-12 questionnaire in 1986 [45, 46] to explore the aspects of physical health, mental health, and environmental adaptability [47]. Later on, scholars revised the survey according to the current situation and developed different question scales consisting of 20, 16, and 13 items [47], and they started to explore the COVID-19 issue [12, 47–51]. Therefore, the scale has gradually developed into a research tool for exploring physical and mental health issues in the context of the COVID-19 epidemic.

According to statistics, in terms of the current status of COVID-19-related research, the areas of research include virus transmission and community infection [4, 32], the impact of economic and social development [1, 2, 16], biology and sports medicine [5, 6, 9, 49, 52], epidemic prevention and decision-making [8, 11, 19, 40], public health [10, 12, 15, 41], psychology [17, 18, 41, 48], and the impact on people's physical and mental health during an epidemic [10, 12, 14, 40]. However, few studies have used the perspective of leisure exercise to explore individual physical and mental health maintenance measures [8] and future research development trends [53]. Although physical and mental health scales have gradually been developed in response to the COVID-19 epidemic, few researchers have explored the impact of recreational exercise on physical and mental health in the context of COVID-19 [54, 55]. Therefore, this study suggested that the development of research on the impact of recreational sports on physical and mental health could help the government or the public to develop personal preventive measures and public health education in the face of global epidemic diseases in the future.

Given the situation, the framework and questions of the physical and mental health scales were developed based on the above literature [1, 2, 4, 10, 12, 21, 23, 29, 32, 37, 39, 47, 49–59] and adapted from relevant studies [54, 55] regarding the current COVID-19 situation. The structural equation model was used to validate the scale and investigate the regulation of recreational sports behavior on the physical and mental health of the elderly under the COVID-19 epidemic, in order to improve the research on COVID-19 and provide a reference for relevant targets, industries, organizations, and researchers.

2.3. Review of Relevant Studies and Hypotheses. Recreational sports behavior can be understood from the viewpoints of leisure frequency, leisure time, leisure intensity, etc. [38]. Good recreational exercise habits can maintain physical and mental health [40]. Recreational sports behavior affects personal quality of life mainly through individuals' psychological and physiological health status [60]. People with adequate exercise intensity can prevent high-risk health hazards [61]. Adopting artificial intelligence to develop exercise prescription or exercise management systems to help people engage in various leisure sports is a trend [33] that meets the current lifestyle and health needs of general and senior citizens. There is a correlation between exercise intensity and physical and mental health, especially for higher levels of involvement, which can result in less emotional distress and suicidal behavior [62]. Although the intensity of exercise may affect health, consistent exercise behavior can help maintain sustainable physical and mental health [61]. Therefore, the first question of this study was whether different exercise intensities have an effect on the physical and mental health of the elderly when using sports apps.

The duration of recreational exercise affects the effectiveness of the exercise, and the existence of regular exercise habits can have a positive effect on maintaining health [39]. Studies have shown that exercise can improve quality of life and psychological health [63], and the duration of exercise is positively correlated with physical and mental health status [64, 65]. Therefore, the second question of this study was whether the difference in the time spent on exercise has an effect on the physical and mental health of the elderly when using sports apps.

Regular exercise planning is essential to achieve good physical and mental health, and good recreational exercise frequency will affect physical and mental health [65]. However, research has shown that appropriate exercise frequency has a slight effect on physical and mental health [66, 67], and it has been shown that exercise frequency has a significant effect on physical and mental health [67]. It could be inferred that the frequency of engaging in leisure sports is related to physical and mental health; therefore, the third question of this research was whether differences in the frequency of exercising using an exercise app have an effect on the physical and mental health of the elderly.

COVID-19 is a major public safety event [1–3] and a global problem that is difficult to solve [11, 12]. The most fundamental solution to prevent the spread of COVID-19 is to make sure that people have the means to fight against the virus, in addition to making good public health decisions [20]. In order to resist the virus, it is important to have good physical and mental health [20], and good physical and mental health can start with the maintenance of recreational exercise [40]. Studies have shown that people with regular exercise habits have better health maintenance effects [39] and that adequate time, frequency, and intensity of exercise can help people maintain their physical and mental health [60, 61] and have a good quality of life. However, according to research findings [2, 4,21, 24, 29, 32, 37, 39, 40, 42, 43, 45, 47, 49, 51, 53, 57, 59, 68], few studies have investigated the impact of recreational exercise and physical and mental health in the context of COVID-19 [54, 55]. Therefore, researchers believe that understanding the influence of leisure exercise on the physical and mental health of the elderly in the COVID-19 infectious environment can make a significant contribution by providing decision-making advice to the government and the public in the event of major infectious disease outbreaks in the future.

3. Methods and Instruments

3.1. Study Framework and Hypotheses. After reading the literature [20, 21, 23, 30, 32, 38, 57, 59, 69], the researcher first went to major sports parks in the north to conduct fieldwork. The researcher first observed the types of sports in which the elderly engaged and then summarized the current types of sports for the elderly based on the survey results. Next, the questionnaire tools were compiled based on the literature [10, 15, 40, 41, 55], the Delphi method was used to test the content validity, and Analysis of Moment Structures 20.0 and Statistical Product and Service Solutions 22.0 for Windows 22.0 statistical software package were used to perform CFA analysis to test the reliability. After the questionnaire tool was used, it was distributed. Statistical verification was used to analyze 711 formal questionnaires, and the results were compared with the content of the interviews. Finally, multiple verification methods were used to discuss.

As illustrated in the study framework, the hypotheses of the study are as follows, as shown in Figure 1:

H1: when exercising with sports apps, different exercise intensities have a significant impact on improving the physical and mental health of the elderly

H2: when exercising with sports apps, different exercise times have a significant impact on improving the physical and mental health of the elderly

H3: when exercising with sports apps, different exercise frequencies have a significant impact on improving the physical and mental health of the elderly

3.2. Research Objects. The study population was the residents of northern Taiwan. Because of the COVID-19 epidemic, sample information can only be collected through the Internet platform. Therefore, a questionnaire survey was used to select subjects by intentional sampling for the study of a specific population group and to obtain a larger number of samples by snowball sampling. After 39 invalid questionnaires were removed from the total 750 questionnaires, 711 valid questionnaires were collected with a recovery rate of 94.8%. The valid questionnaires were coded and analyzed by SPSS 22.0 statistical software for documentation and descriptive analysis of demographic variables. Finally, the research will use AMOS 20.0 software to analyze the number of samples and analyze the results by means of test statistics.

3.3. Research Tools. The purpose of this study was to investigate the effects of recreational sports behavior on physical and mental health during the COVID-19 epidemic. Using a questionnaire survey, we deduced similar results of the positive effects of recreational sports behavior on physical and mental health compared to the research findings [20, 21, 23, 38–44], which will manifest in the current uncertainty of the epidemic. The content of the questionnaire consisted of three parts, namely, background variables, recreational sport behaviors, and physical and mental health effects. The background variables [8, 11–15] contained three questions in total. With reference to previous studies [60, 61, 63, 64, 66, 67], a total of three questions were compiled for the modes of recreational sports behaviors. Seventeen questions were compiled to investigate the physical and mental health impact [10, 12, 15, 40, 41, 55] and a total of 23 questions were included in the questionnaire, as shown in Figure 2.

In consideration of the five-point scale, a score of one to five points was designed, in which one represents total disagreement and five represents total agreement. The interviewees were invited to provide feedback on the research questions. The demographic variables included gender (male, female) and education level (elementary school, secondary school, high school, college/university, institute (inclusive) and above). The recreational sport behavior was characterized in terms of its duration, frequency, and intensity. Leisure exercise time was categorized as none, within 30 minutes, one hour, one to three hours, and more than three hours. The frequency of leisure exercise was categorized as none, at least one time per day, at least one time per week, and more than one time per month or more. The intensity of leisure exercise was categorized as mild intensity (including no intensity), low intensity, medium intensity, medium–high intensity, and very high intensity. Physical and mental health effects included psychological feelings, mental state, physical state, negative thoughts, and other four components, as shown in Table 1.

Under the pressure of the epidemic transmission environment and other constraints, 50 questionnaires were distributed from May 1 to 5, 2020, to test the data. After deleting the invalid questionnaires, the data were coded, documented using SPSS 22.0, and then analyzed using AMOS 20.0 to determine the feasibility of the questionnaire.

3.4. Offending Estimate. The error variance values in this study ranged from 0.01 to 0.03, and the standardized coefficients ranged from 0.67 to 0.95 but did not exceed 0.95. This result is consistent with the standard of the offending estimate test that is to determine whether there is a negative error variance and whether the standardized regression coefficient exceeds or is too close to 1 [70]. Therefore, it means that the results of these data do not violate the estimation and can be tested for the overall model fitness, as shown in Table 2.

4. Measurement Mode Analysis

4.1. Verification of Convergent Validity. In this study, the convergent reliability of the mode was measured using the standardized path coefficient, average variance extracted, and composite reliability. In general, the composite reliability should be greater than 0.60, and the mean number of variances sampled should be greater than 0.50 [60]. After confirmatory factor analysis and obtaining standardized parameter estimates, as shown in Table 3, the psychological perceptions ranged from 1.00 to 1.12; mental status ranged from 1.00 to 1.08; physical status ranged from 0.87 to 1.00; and negative thoughts ranged from 0.87 to 1.00. The

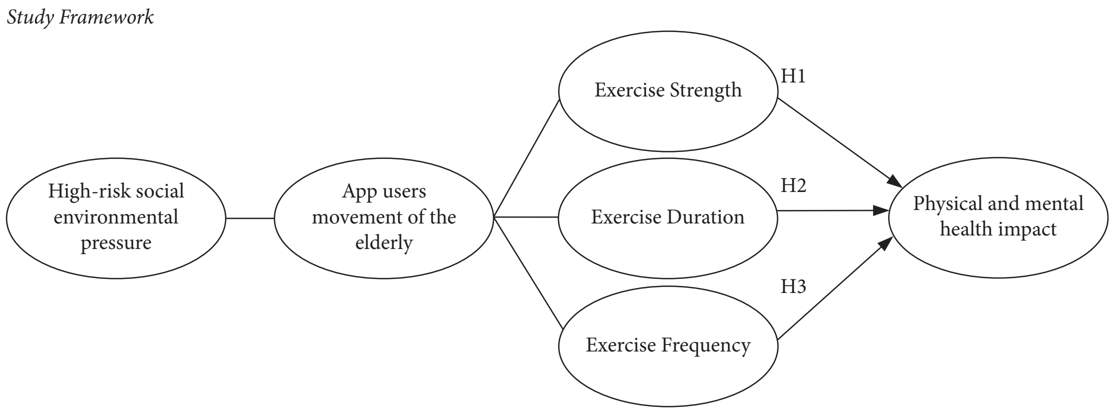


Figure 1: Study framework.

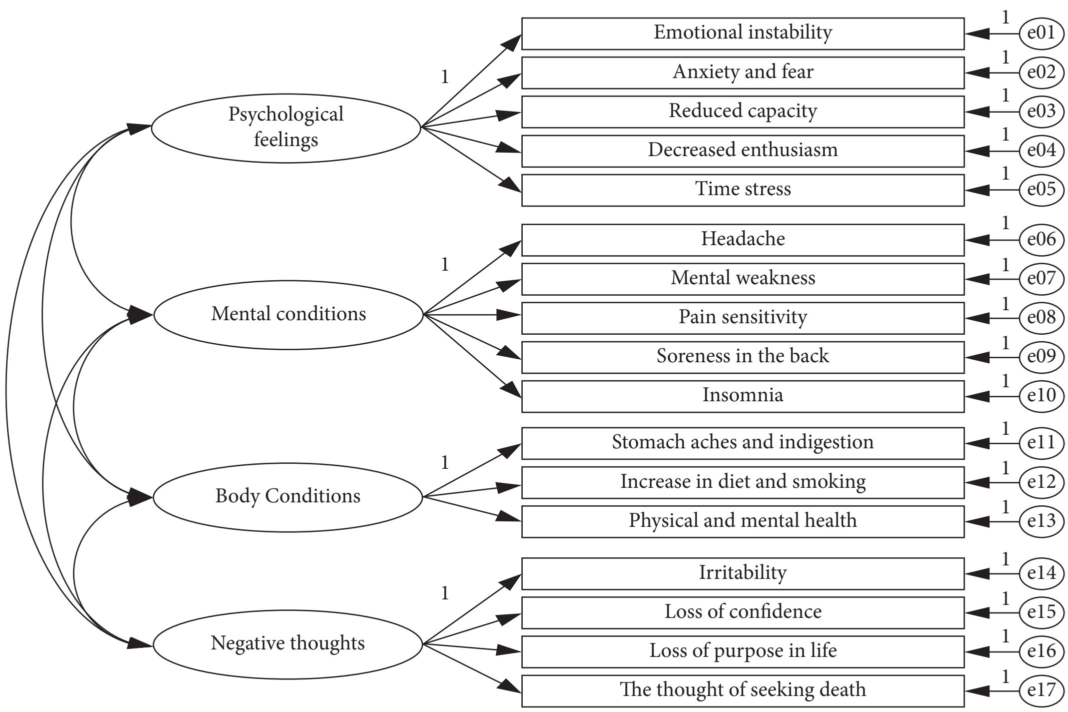


Figure 2: Confirmatory factor analysis framework of the physical and mental health scale.

composite reliability values of the four potential parameters psychological feelings, mental state, physical state, and negative thoughts were 0.80, 0.95, 0.86, and 0.86, respectively, all greater than 0.60. The mean variance extracted values were 0.66, 0.90, 0.76, and 0.75, respectively, all greater than 0.50. These results indicated that the mode had good inner quality and convergent validity.

4.2. Discrimination of Validity Verification. The structural mode analysis in this study was performed using a $\chi 2$ check and the following indices: $\chi 2$ to degrees of freedom ratio, GFI, AGFI, RMSEA, CFI, and PCFI [60]. After the mode correction of the physical and mental health impact scale, the GFI was 0.98, AGFI was 0.95, RMSEA was 0.15, CFI was 0.99, and PCFI was 0.50. All the fit indices met the mode fitness criteria, which indicated that the results of this study were an acceptable mode, as shown in Table 4.

After completion of the questionnaire, 711 responses were collected between May 20 and June 20, 2020, using the intentional sampling method to select the target participants. SPSS 22.0 statistical software was used for the descriptive analysis of the demographic variables. Then, semistructured interviews were conducted with three scholars who had backgrounds in recreational sports, medical care, and health protection, as well as two elderly sports enthusiasts, to obtain their opinions on the analysis results. This paper was subsequently constructed in the order of induction, organization, and analysis [61]. Finally, a multidimensional approach was adopted to combine information from different research subjects, research theories, and methods by examining multiple pieces of data from

Table 2: Estimation checklist for the violation of leisure sports behavior on the physical and mental health scale.

Questions	Standardized regression coefficient	Error variance
Emotional instability<--- Psychological feelings	0.76	0.03
Anxiety and fear<--- Psychological feelings	0.67	0.03
Reduced capacity<--- Psychological feelings	0.84	0.02
Decreased enthusiasm<--- Psychological feelings	0.79	0.03
Time stress<--- Psychological feelings	0.78	0.03
Headache<--- Mental conditions	0.72	0.03
Mental weakness<--- Mental conditions	0.78	0.02
Pain sensitivity<--- Mental conditions	0.85	0.02
Soreness in the back<--- Mental conditions	0.94	0.01
Insomnia<--- Mental conditions	0.95	0.01
Stomach aches and indigestion<--- Body conditions	0.95	0.01
Increase in diet and smoking<--- Body conditions	0.78	0.03
Feeling stiff and tight<--- Body Conditions	0.69	0.03
Irritability<--- Negative thoughts	0.85	0.02
Loss of confidence<--- Negative thoughts	0.94	0.01
Loss of purpose in life<--- Negative thoughts	0.90	0.01
The thought of seeking death<--- Negative thoughts	0.79	0.02

Table 3: Convergent reliability and mean variance extracted values of the impact of recreational sports behavior on physical and mental health scale.

Questions	Standardized loading	Nonstandardized loading	SE	CR (t-value)	P	SMC	CR	AVE
Decreased enthusiasm<--- Psychological feelings	1.00	0.81				0.65	0.80	0.66
Time stress<--- Psychological feelings	1.12	0.82	0.08	14.51	***	0.67		
Soreness in the back<--- Mental conditions	1.00	0.92				0.85	0.95	0.90
Insomnia<--- Mental conditions	1.08	0.98	0.02	51.42	***	0.95		
Stomach aches and indigestion<--- Body conditions	1.00	0.95				0.91	0.86	0.76
Increase in diet and smoking<--- Body conditions	0.87	0.79	0.03	30.21	***	0.62		
Loss of confidence<--- Negative thoughts	1.00	0.94				0.88	0.86	0.75
The thought of seeking death<--- Negative thoughts	0.88	0.79	0.03	27.85	***	0.63		

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

Table 4: Fitness analysis of the impact of recreational sports behavior on the physical and mental health scale study mode.

Fit indices	Acceptance criteria	Mode (before correction)	Mode (after correction)	Fitness determination
χ^2 (Chi-square)	Smaller the better	1901.28	52.10	
χ^2/degree of freedom	<3	16.83	3.72	Fit
GFI	>0.90	0.73	0.98	Fit
AGFI	>0.90	0.64	0.95	Fit
RMSEA	<0.08	0.15	0.06	Fit
CFI	>0.90	0.85	0.99	Fit
PCFI	>0.50	0.71	0.50	Fit

multiple perspectives and comparing the results of different studies [63], in order to obtain accurate knowledge and meaning.

5. Research Results

5.1. Sample Descriptive Statistics. A total of 711 respondents were interviewed in the study. Most of them were female (451 or 63.4%), while 260 or 36.6% were male. In terms of education, the majority had a college education (536 or 75.4%), while primary education accounted for the least (1.7%). Finally, most of them are engaged in Chinese Kung Fu (for example: Tai Chi) and fitness exercises (34%), and a small number of elderly people choose to engage in social dance (for example: aerobic dance) exercises (7%). The results are shown in Table 5.

5.1.1. Analysis of the Regulatory Power of the Influence of Different Leisure Exercise Intensities on Physical and Mental Health. According to the literature, adequate leisure exercise intensity can improve the quality of life of individuals [61, 71],

Table 5: Respondents' demographics.

Variable	Classification	Quantity	(%)
Gender	Male	260	36.6
	Female	451	63.4
Education level	Elementary school	12	1.7
	Secondary school	33	4.6
	High school	112	15.8
	College/university	536	75.4
	Institute (inclusive) and above	18	2.5
Kind	No	110	15.4%
	Ball	163	22.9%
	Dance class	49	7%
	Fitness class	106	14.8%
	Leisure	42	5.9%
	Qigong or literary	241	34%

which can be seen in terms of both psychological and physiological health aspects [61]. Based on this result, the researcher proposed hypothesis 1 (exercise intensity has an impact on improving physical and mental health). As shown in Table 6, leisure exercise intensity was classified into five categories: nonexercise, low intensity, low intensity, medium intensity, high intensity, and very high intensity. Statistical tests were used to analyze the effects of enthusiasm. It was found that enthusiasm was most affected by those with very high intensity (1.79), medium–high intensity (2.92), and no exercise (3.14). Those who exercised at light intensity (2.67), low intensity (3.40), medium intensity (2.85), and very high intensity (1.79) felt the most pressured by time. The results were not entirely consistent with the assumptions.

The effects of different exercise intensities on psychological perception, mental status, physical status, and negative thoughts were further investigated. It was found that low-intensity exercise had the greatest effect on the psychological aspects of physical and mental health ($M = 3.30$), while those who did not exercise had the greatest effect on negative thoughts ($M = 2.19$), mental condition ($M = 2.41$), and physical condition ($M = 3.95$), as shown in Figure 3.

According to the results, this result was different from that expected research hypothesis 1. When exercising with sports apps, different exercise intensities have a significant effect on improving the physical and mental health of the elderly.

5.1.2. Analysis of the Regulatory Power of the Influence of Leisure Sports Time on Physical and Mental Health. Adequate exercise time planning can improve physical and mental health [39, 69], and duration is a key factor [61]. Based on this result, the researcher proposed hypothesis 2 (exercise time has an impact on improving physical and mental health). As shown in Table 7, leisure exercise time was divided into five categories: none, less than 30 minutes, one hour, one to three hours, and more than three hours. Therefore, after statistical analysis, it was found that individuals who planned one hour of exercise (3.06) felt the greatest influence on enthusiasm; those who planned less than 30 minutes (2.88), one to three hours (2.71), and more than three hours (3.47) felt the most pressured by time, while those who did not exercise lost their confidence (2.19) and had suicidal thoughts (2.19).

The psychological perception, mental condition, physical condition, and negative thoughts of the participants were further investigated according to the different exercise times. It was found that those who planned exercise for more than three hours showed the greatest influence on psychological feeling ($M = 3.445$), mental condition ($M = 2.985$), and physical condition ($M = 2.955$), while those who did not exercise showed the most significant influence on negative thoughts ($M = 2.19$), as shown in Figure 4.

According to the results, this result was different from that expected by research hypothesis 2. When exercising with sports apps, different exercise time has a significant effect on improving the physical and mental health of the elderly.

5.1.3. Analysis of the Regulatory Power of the Influence of Leisure Exercise Frequency on Physical and Mental Health. Regular exercise habits can achieve the effect of maintaining health [39, 69], and the length of time is the key. Based on this result, the researchers proposed hypothesis 3 (exercise frequency has an impact on improving physical and mental health). As shown in Table 8, the frequency of leisure exercise was divided into five categories: none, at least once a day, at least once a week, at least once a month, and more than once a month. After statistical analysis, it was found that the enthusiasm of those who exercised once a week (2.85) and those who did not exercise (1.25) were the most influenced by the frequency of exercise, while those who exercised once a day (2.94) and once a month (3.86) felt the most pressured by time.

Next, psychological perception, mental condition, physical condition, and negative thoughts were examined according to exercise frequency. It was found that those who planned exercise once a month showed the most significant effect on their psychological feeling ($M = 3.725$), negative thoughts ($M = 3.205$), and mental ($M = 3.34$) and physical condition ($M = 3.23$), as shown in Figure 5.

According to the results, this result was different from that expected by research hypothesis 3. When exercising with sports apps, different exercise frequencies have a significant effect on improving the physical and mental health of the elderly.

Table 6: Analysis of the physical and mental health perceptions of elderly people with different exercise intensity behaviors.

Facet	Issue	No exercise	Light intensity	Low intensity	Medium intensity	Medium to high intensity	Very high intensity
Psychological feelings	Decreased enthusiasm	3.14☆	2.56	3.20	2.74	2.92☆	1.79☆
	Time stress	3.05	2.67☆	3.40☆	2.85☆	2.58	1.79☆
Mental conditions	Soreness in the back	2.48	2.17	2.30	2.04	1.67	1.53
	Insomnia	2.33	2.17	2.30	2.04	1.67	1.55
Body conditions	Stomach aches and indigestion	2.33	2.33	2.10	1.93	1.75	1.53
	Increase in diet and smoking	2.29	2.06	2.10	1.85	1.58	1.46
Negative thoughts	Loss of confidence	2.19★	2.11	1.90	1.81	1.42★	1.46
	The thought of seeking death	2.19★	1.94★	1.70★	1.78★	1.42★	1.40★

☆ = high perception；★ = minimal perception.

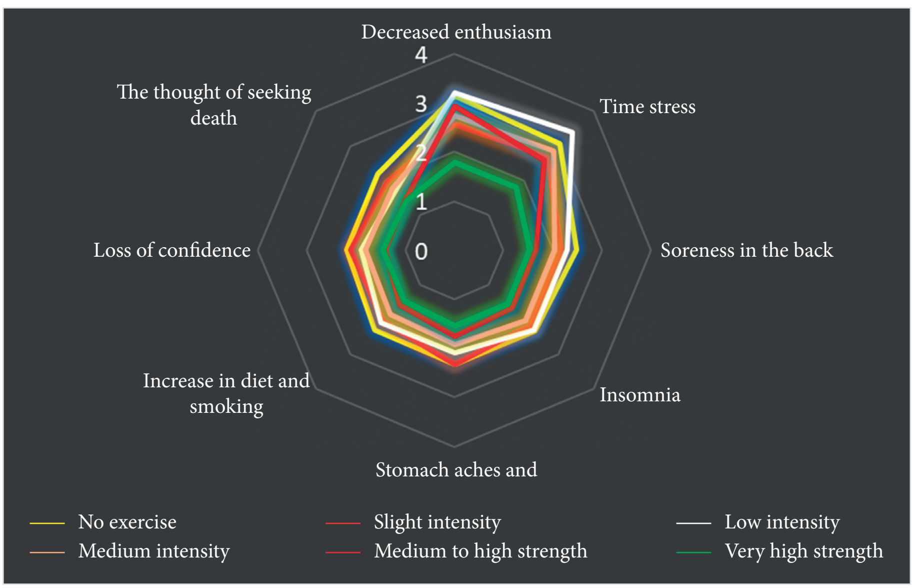


Figure 3: Analysis of the effects of different exercise intensities on psychological feelings, mental status, physical status, and negative thoughts.

Table 7: Analysis of physical and mental health perceptions of the elderly with different exercise behaviors.

Facet	Issue	No exercise	Within 30 minutes	1 hour	1–3 hours	More than 3 hours
Psychological feelings	Decreased enthusiasm	1.27	2.73	3.06☆	2.52	3.42
	Time stress	1.20	2.88☆	2.91	2.71☆	3.47☆
Mental conditions	Soreness in the back	1.13	2.08	2.13	1.92	2.95
	Insomnia	1.12	2.00	2.13	1.94	3.02
Body conditions	Stomach aches and indigestion	1.11★	2.00	2.13	1.87	3.00
	Increase in diet and smoking	1.11★	1.69★	1.91	1.75★	2.91
Negative thoughts	Loss of confidence	2.19☆	2.11	1.90	1.81	1.42★
	The thought of seeking death	2.19☆	1.94	1.70★	1.78	1.42★

☆ = high perception；★ = minimal perception.

6. Results and Discussion

The aim of this study was to investigate the modulating effect of recreational sports behaviors on the physical and mental health of the elderly during the COVID-19 epidemic. Three hypotheses were established based on the literature [20, 39, 40, 60, 61, 64, 67], and a questionnaire survey was conducted to analyze the results of the study. Semistructured interviews were then conducted with three scholars who had backgrounds in recreational sports, medical care, and health

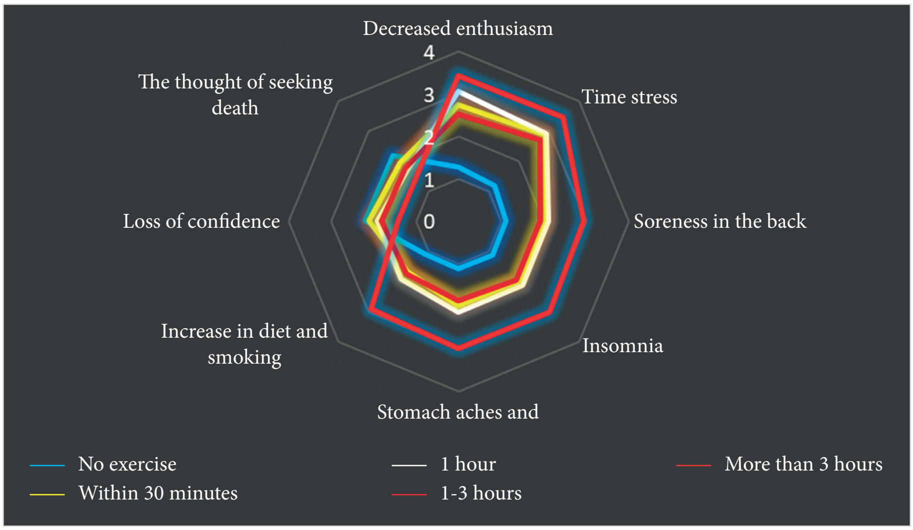


Figure 4: Analysis of the effects of different exercise durations on psychological feelings, mental state, physical state, and negative thoughts.

Table 8: Analysis of physical and mental health perceptions of elderly people with different exercise frequencies.

Facet	Issue	No exercise	Once a day	Once a week	Once a month
Psychological feelings	Decreased enthusiasm	1.25☆	2.81	2.85☆	3.59
	Time stress	1.21	2.94☆	2.68	3.86☆
Mental conditions	Soreness in the back	1.13	2.15	2.00	3.36
	Insomnia	1.12	2.23	1.96	3.32
Body conditions	Stomach aches and indigestion	1.12	2.15	1.96	3.32
	Increase in diet and smoking	1.13	2.01	1.75	3.14★
Negative thoughts	Loss of confidence	1.11★	2.03	1.68	3.18
	The thought of seeking death	1.11★	1.85★	1.57★	3.23

☆ = high perception； ★ = minimal perception.

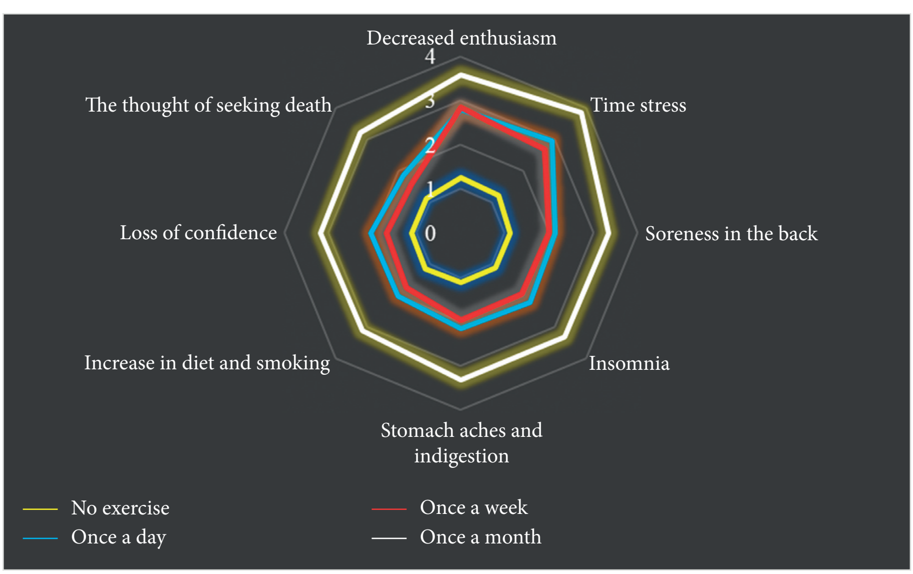


Figure 5: Analysis of the effects of different exercise frequencies on psychological feelings, mental status, physical status, and negative thoughts.

protection, as well as two elderly sports enthusiasts, to obtain their opinions on the analysis results. This paper was subsequently constructed in the order of induction, organization, and analysis in a rigorous manner [72]. Finally, a multidimensional approach was adopted to combine information from different research subjects, research theories, and methods by examining multiple data from multiple perspectives and comparing the results of different studies [73, 74], in order to obtain accurate knowledge and meaning.

6.1. Leisure Exercise Intensity. Although researchers have suggested that exercise intensity has an impact on health [60, 61, 63], for the elderly, higher intensity represents a greater level of commitment and dedication to exercise. As such, their bodies may no longer easily handle the intensity, and their enthusiasm may be compromised due to insufficient time and restricted environments during the epidemic. Moreover, the participants who did not exercise at all or exercised at a low intensity were constantly limited in space and time and had no proper way to relieve stress, making them more sensitive than others in terms of their physical and mental health. As a result, the enthusiasm of people with very high intensity, moderate to high intensity, and no exercise was affected. People who exercised at light, low, moderate, and very high intensities were pressured by time. It was also found that low-intensity exercise had the greatest psychological impact, while those who did not exercise had serious negative thoughts, as well as mental and physical health problems. Therefore, this study concluded that when the environmental pressure is high, the intensity of exercise may not have an impact on the improvement of the physical and mental health of the elderly, which was not entirely consistent with hypothesis 1.

6.2. Leisure Exercise Time. Studies have confirmed that long-term exercise planning can improve health [39, 64, 65], and it is believed that adequate exercise duration can improve health; however, because of the deterioration of physical and psychological performance and the reduced mobility of the elderly, the need for adequate time to engage in exercise may be restricted due to the current environmental pressure. In addition, those who did not exercise usually had few ways to relieve stress, and those who exercised for a short period had to take time away from work or family life to exercise. Due to the COVID-19 epidemic, the exercise environment is confined and exercise times are limited, which deprive people of finding relief. The enthusiasm of those who planned for one hour of exercise was most affected; those who planned for 30 minutes, one to three hours, or more than three hours felt the greatest pressure by the time, and those who did not exercise were likely to lose confidence and have suicidal thoughts. Furthermore, it was found that the psychological feelings and the mental and physical conditions of those who planned to exercise for more than three hours had the greatest influence, while those who did not exercise had the most obvious negative thoughts. Therefore, the present study concluded that as the amount of environmental stress increases, the duration of exercise may not be fully effective in improving the physical and mental health of the elderly.

6.3. Leisure Exercise Duration. Although regular exercise frequency can improve health [39], the elderly participants who had regular exercise frequency already included exercise as part of their daily life; however, their lives were affected by external environmental constraints and the limited time for leisure exercise. All these factors disrupted the existing planning and led to the shortening or even cancellation of exercise planning for the elderly. The enthusiasm of those who exercised once a week and those who did not exercise was affected the most, and the time pressure of those who exercised once a day and once a month was the most noticeable. It was also found that the effect of exercising once a month was most evident on the aspects of psychological feelings, negative thoughts, and mental and physical conditions. Therefore, the present study concluded that as the environmental stress level increases, the frequency of physical activity among the elderly does not have a direct correlation with the improvement of physical and mental health.

7. Conclusions and Suggestions

The research and investigation of this study found that when the elderly are in a high-risk social environment, although they may use sports apps to exercise, the intensity and time involved in exercise will be affected, but they will not change the frequency of exercise if it has become a daily habit. The elderly who exercise at intervals of one month are more physically and mentally stressed, but different exercise frequencies also result in different levels of physical and mental health problems; the lower the exercise intensity, the more obvious the negative emotions, the stronger or the less time they spend exercising, and the greater the exercise pressure they must face.

The following suggestions were proposed based on the aforementioned results.

7.1. For the Elderly. The elderly should combine their existing living environment with online exercise education courses to change the current exercise pattern and satisfy the demand and quality of exercise. They should also try to make up for the shortage of exercise time by planning intermittent exercise.

7.2. For the Government. In high-tension environments, governments should integrate local administrative manpower or work with community organizations to care for the physical and mental health of those who are unwilling or unable to exercise.

7.3. For Future Studies. Future studies should attempt to understand the different types of exercise for individuals with different workout schedules and continue to explore the effects of high-tension environments on physical and mental health. Researchers should also continue to explore the issue by focusing on different regions, countries, or genders.

Data Availability

Data are available on request to the authors. The data source is obtained from the questionnaire analysis of the authors' research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] A. Atkeson, "What will be the economic impact of COVID-19 in the US? Rough estimates of disease scenarios," 2020. NBER Working Paper, Article ID 26867.

[2] W. J. McKibbin and R. Fernando, "The global macroeconomic impacts of covid-19: seven scenarios," *CAMA Working Paper)*, vol. 19, pp. 1–45, 2020.

[3] WHO, *Coronavirus Disease 2019 (COVID-19) Situation Report −67,* 2020, http://apps.who.int/iris/bitstream/handle/10665/331613/nCoVsitrep27Mar2020-eng.pdf.

[4] Systems Science and Engineering, *COVID-19 Dashboard*, Johns Hopkins University, Baltimore, MA, USA, 2020, https://gisanddata.maps.arcgis.com/apps/opsdashboard/index.html#/bda7594740fd40299423467b48e9ecf6.

[5] W. H. Maya, "How does COVID-19 quietly take away the patient's oxygen?," 2020, https://www.natgeomedia.com/science/article/content-11250.html?fbclid=IwAR3RwjbEa8oO_iR7hqMYyw_zQ1fY3fNssVcub1p_EGkG7C1ZYkG8lApKPYQ.

[6] Z. Xu, L. Shi, Y. Wang et al., "The epidemiological characteristics of an outbreak of 2019 novel coronavirus diseases (COVID-19) in China," *Case Report*, vol. 8, no. 4, pp. 420–422, 2020.

[7] Y. C. Chen, P. E. Lu, and C. S. Chang, "A time-dependent SIR model for COVID-19 with undetectable infected persons," 2020, https://arxiv.org/pdf/2003.00122.pdf.

[8] P. Kilgore, *The COVID-19 Survival Guide: Information and Practical Steps You Can Use to Protect Yourself against the Coronavirus*, Quantitative Health, LLC, California, CA, USA, 2020.

[9] Y. Liu, A. A. Gayle, A. Wilder-Smith, and J Rocklöv, "The reproductive number of COVID-19 is higher compared to SARS coronavirus," *Journal of Travel Medicine*, vol. 27, no. 2, pp. 1–21, 2020.

[10] W. Samantha and G. R. Geek, "Half of Americans suffering mental health issues during coronavirus, new poll shows," *Forbes*, pp. 25–30, 2020.

[11] C.-H. Hsu, H.-H. Lin, C.-C. Wang, and S. Jhang, "How to defend COVID-19 in taiwan? Talk about people's disease awareness, attitudes, behaviors and the impact of physical and mental health," *International Journal of Environmental Research and Public Health*, vol. 17, no. 13, p. 4694, 2020.

[12] Y.-J. Kim, J.-H. Cho, and E.-S. Kim, "Differences in sense of belonging, pride, and mental health in the daegu metropolitan region due to COVID-19: comparison between the presence and absence of national disaster relief fund," *International Journal of Environmental Research and Public Health*, vol. 17, no. 13, p. 4910, 2020.

[13] S. K. Brooks, R. K. Webster, L. E. Smith et al., "The psychological impact of quarantine and how to reduce it: rapid review of the evidence," *The Lancet*, vol. 395, no. 10227, pp. 912–920, 2020.

[14] M. Douglas, S. V. Katikireddi, M. Taulbut, M. McKee, and G. McCartney, "Mitigating the wider health effects of covid-19 pandemic response," *BMJ*, vol. 369, p. m1557, 2020.

[15] D. Stuckler, S. Basu, M. Suhrcke, A. Coutts, and M. McKee, "The public health effect of economic crises and alternative policy responses in Europe: an empirical analysis," *The Lancet*, vol. 374, no. 9686, pp. 315–323, 2009.

[16] Australian Government Department of Health, *Coronavirus (COVID-19)*, https://www.health.gov.au/health-topics/novel-coronavirus-2019-ncov, 2020.

[17] L. Lai, *Fear and Panic Can Do More Harm than the Coronavirus, Says PM Lee HsienLoong*, https://www.straitstimes.com/singapore/fear-and-panic-can-do-more-harm-than-the-coronavirus-says-pm-lee-hsien-loong, 2020.

[18] X. Zhou, C. L. Snoswell, L. E. Harding et al., "The role of telehealth in reducing the mental health burden from COVID-19," *Telemedicine and e-Health*, vol. 26, no. 4, pp. 377–379, 2020.

[19] Scottish Government, *A Connected Scotland: Our Strategy for Tackling Social Isolation Andloneliness and Building Stronger Social Connections*, 2018.

[20] W. Weiten and M. A. Lloyd, *Psychology Applied to Modern Life: Adjustment in the 90s*, Brooks, Seattle, WA, USA, 4th edition, 1994.

[21] Y. G. Huang, H. L. Li, and H. Z. Cheng, "The prevention of dementia by exercise and its influence on physiology and psychology," *NCYU Physical Education, Health & Recreation Journal*, vol. 11, no. 1, pp. 272–277, 2012.

[22] Y. R. Huang, "Exercise and upper respiratory tract infection," *Quarterly of Chinese Physical Education*, vol. 7, no. 4, pp. 104–109, 1994.

[23] C. C. Chang, C. Liang, C. F. Yan, and J. S. Tseng, "Research on the impact on the convenience and curiosity of continued intention of learning English in the mobile learning environment," *Journal of Educational Media & Library Sciences*, vol. 48, no. 4, pp. 571–588, 2011.

[24] R. M. Yılmaz and Y. Göktaş, "Using augmented reality technology in education," *Cukurova University Faculty of Education Journal*, vol. 47, no. 2, pp. 510–537, 2018.

[25] R. Barouki, P. D. Gluckman, P. Grandjean, M. Hanson, and J. J. Heindel, "Developmental origins of non-communicable disease: implications for research and public health," *Environmental Health*, vol. 11, no. 1, p. 42, 2012.

[26] A. J. Bandodkar, I. Jeerapan, and J. Wang, "Wearable chemical sensors: present challenges and future prospects," *ACS Sensors*, vol. 1, no. 5, pp. 464–482, 2016.

[27] C.-H. Hsu, H.-H. Lin, and S. Jhang, "Sustainable tourism development in protected areas of rivers and water sources: a case study of Jiuqu Stream in China," *Sustainability*, vol. 12, no. 13, p. 5262, 2020a.

[28] S. Pierce, K. Erickson, and M. Sarkar, "High school student-athletes' perceptions and experiences of leadership as a life skill," *Psychology of Sport and Exercise*, vol. 51, Article ID 101716, 2020.

[29] J. Taha, J. Sharit, and S. Czaja, "Use of and satisfaction with sources of health information among older internet users and nonusers," *The Gerontologist*, vol. 49, no. 5, pp. 663–673, 2009.

[30] J. W. Li, Y. C. Chang, M. X. Xu, and D. Y. Huang, "A health management service with beacon-based identification for preventive elderly care," *Journal of Information Processing Systems*, vol. 16, no. 3, pp. 648–662, 2018.

[31] D. Bastos, J. Ribeiro, F. Silva et al., "SmartWalk mobile - a context-aware m-health app for promoting physical activity among the elderly," in *Proceedings of the World Conference on*

Information Systems and Technologies (WorldCIST'19 2019): New Knowledge in Information Systems and Technologies, pp. 829–838, Springer, Galicia, Spain, April 2019.
[32] I. Moric, S. Pekovic, and J. Jovanovic, "Digital health literacy and sport-physical activities: the moderating role of age," *Health Policy*, pp. 1–24, 2020.
[33] J. H. Yu, H. H. Lin, J. M. Huang, C. H. Wu, and K. C. Tseng, "Under industry 4.0, the current status of development and trend sports industry combining with cloud technology," *Mathematical Problems in Engineering*, vol. 2020, Article ID 3805373, 16 pages, 2020.
[34] S. Zhang, "Industry 4.0 and smart manufacturing," *Journal of Mechanical Design and Manufacturing Engineering*, vol. 43, no. 8, pp. 1–5, 2014.
[35] Y. Abdourazakou, N. Lorgnier, S. O'Rourke, N. O'Reilly, and G. Abeza, "Fans' online services expectations and experiences: the case of national basketball association," *Journal of Sports Science*, vol. 1, pp. 1–14, 2013.
[36] Y. Y. Hung, "Between using these APPs about sports and not using these, and discusses which APP elevates the best results," Master's Thesis, STU of Science and Technology, Kaohsiung, Taiwan, 2014.
[37] W. C. Li, "The study on Fitness APP of continuous use intention survey- A case of cycling," Master's Thesis, NCHU, Department of Information Management Systems, Taichung, Taiwan, 2019.
[38] B. C. Long and C. J. Haney, "Enhancing physical activity in sedentary women: information, locus of control, and attitudes," *Journal of Sport Psychology*, vol. 8, no. 1, pp. 8–24, 1986.
[39] R. Debon, J. D. Coleone, E. A. Bellei, and A. C. B. De Marchi, "Mobile health applications for chronic diseases: a systematic review of features for lifestyle improvement," *Diabetes & Metabolic Syndrome: Clinical Research Reviews*, vol. 13, no. 4, pp. 2507–2512, 2019.
[40] WHO, *Mental Health: Strengthening Our Response*, https://www.who.int/news-room/fact-sheets/detail/mental-health-strengthening-our-response, 2018.
[41] A. Bandura, *Self-efficacy: The Exercise of Control*, W. H. Freeman and Company, New York, NY, USA, 1997.
[42] J. F. Sallis, R. B. Pinski, R. M. Grossman, T. L. Patterson, and P. R. Nader, "The development of self-efficacy scales for healthrelated diet and exercise behaviors," *Health Education Research*, vol. 3, no. 3, pp. 283–292, 1988.
[43] V. Yiengprugsawan, M. Kelly, and B. Tawatsupa, "Kessler psychological distress scale," *Encyclopedia of Quality of Life and Well-Being Research*, Springer, Amsterdam, Netherlands, pp. 3469-3470, 2014.
[44] NSW Health Department, *NSW Mental Health Outcomes Andassessment Training (MH-OAT) Facilitator's Manual*, https://www.health.nsw.gov.au/mentalhealth/resources/Publications/children-facilitator.pdf, 2001.
[45] T.-A. Cheng and P. Williams, "The design and development of a screening questionnaire (CHQ) for use in community studies of mental disorders in Taiwan," *Psychological Medicine*, vol. 16, no. 2, pp. 415–422, 1986.
[46] U. Halbreich and S. Karkun, "Cross-cultural and social diversity of prevalence of postpartum depression and depressive symptoms," *Journal of Affective Disorders*, vol. 91, no. 2–3, pp. 97–111, 2006.
[47] C. M. Chang, Y. L. Chang, Y. L. Lay, and S. P. Chang, "A study on influence of Taoyuan City Taoyuan District elementary school teachers' job stress on perceived health-leisure sports participation level as the moderator variable," *Journal of Management Practices and Principles*, vol. 11, no. 4, pp. 21–38, 2017.
[48] B. Arnout, Z. Al-Dabbagh, N. Al Eid et al., "The effects of corona virus (COVID-19) outbreak on the individuals' mental health and on the decision-makers: a comparative epidemiological study," *International Journal of Medical Research & Health Sciences*, vol. 9, no. 3, pp. 26–47, 2020.
[49] G. Lippi, B. M. Henry, and F. Sanchis-Gomar, "Physical inactivity and cardiovascular disease at the time of coronavirus disease 2019 (COVID-19)," *European Journal of Preventive Cardiology*, 2020.
[50] G. Motta Zanin, E. Gentile, A. Parisi, and D. Spasiano, "A preliminary evaluation of the public risk perception related to the COVID-19 health emergency in Italy," *International Journal of Environmental Research and Public Health*, vol. 17, no. 9, p. 3024, 2020.
[51] M. Sharma, "COVID-19 (An International Trauma): A brief analysis on research trends, impacts and solutions," *International Journal for Research in Applied Sciences and Technology*, vol. 7, 2020.
[52] A. V. Mattioli, S. Sciomer, C. Cocchi, S. Maffei, and S. Gallina, "Quarantine during COVID-19 outbreak: changes in diet and physical activity increase the risk of cardiovascular disease," *Nutrition, Metabolism, and Cardiovascular Diseases*, vol. 30, no. 9, pp. 1409–1417, 2020.
[53] M. H. Taghrir, R. Borazjani, and R. Shiraly, "COVID-19 and Iranian medical students; a survey on their related-knowledge, preventive behaviors and risk perception," *Archives of Iranian Medicine*, vol. 23, no. 4, pp. 249–254, 2020.
[54] D. D. Callow, N. A. Arnold-Nedimala, L. S. Jordan et al., "The mental health benefits of physical activity in older adults survive the COVID-19 pandemic," *American Journal of Geriatric Psychiatry*, vol. 28, no. 10, pp. 1046–1057, 2020.
[55] C. Ranasinghe, C. Ozemek, and R. Arena, "Exercise and well-being during COVID 19 - time to boost your immunity," *Expert Review of Anti-infective Therapy*, vol. 18, no. 12, pp. 1195–1200, 2020.
[56] M. T. Brown, "An analysis on online marketing in the sport industry: user activity, communication objectives, and perceived benefits," *Sport Marketing Quarterly*, vol. 12, no. 1, pp. 48–55, 2003.
[57] Gartner, *Gartner Says Global End-User Spending on Wearable Devices to Total $52 Billion in 2020*, 2019, https://www.gartner.com/en/newsroom/press-releases/2019-10-30-gartner-says-global-end-user-spending-on-wearable-dev.
[58] H.-H. Lin, S.-S. Lee, Y.-S. Perng, and S.-T. Yu, "Investigation about the impact of tourism development on a water conservation area in Taiwan," *Sustainability*, vol. 10, no. 7, p. 2328, 2018.
[59] M. V. Voronina, Z. O. Tretyakova, E. G. Krivonozhkina, S. I. Buslaev, and G. G. Sidorenko, "Augmented reality in teaching descriptive geometry, engineering and computer graphics – systematic review and results of the Russian teachers' experience," *Eurasia Journal of Mathematics, Science and Technology Education*, vol. 15, no. 12, pp. 1–17, 2019.
[60] E. McAuley, J. F. Konopack, R. W. Motl, K. S. Morris, S. E. Doerksen, and K. R. Rosengren, "Physical activity and quality of life in older adults: influence of health status and self-efficacy," *Annals of Behavioral Medicine*, vol. 31, no. 1, pp. 99–103, 2006.
[61] A. Downs and J. Ashton, "Search.proquest.comVigorous physical activity, sports participation, and athletic identity: implications for mental and physical health in college

students," *Journal of Sport Behavior*, vol. 34, no. 3, pp. 228–249, 2011.

[62] P. A. Harrison and G. Narayan, "Differences in behavior, psychological factors, and environmental factors associated with participation in school sports and other activities in adolescence," *Journal of School Health*, vol. 73, no. 3, 2009.

[63] M. Kim, A. C. H. Kim, J. I. Newman, G. R. Ferris, and P. L. Perrewé, "The antecedents and consequences of positive organizational behavior: the role of psychological capital for promoting employee well-being in sport organizations," *Sport Management Review*, vol. 22, no. 1, pp. 108–125, 2019.

[64] J. K. Ihalainen, A. Inglis, T. Mäkinen et al., "Strength training improves metabolic health markers in older individual regardless of training frequency," *Frontiers in Physiology*, vol. 10, no. 32, p. 32, 2019.

[65] M. Maselli, E. Gobbi, M. Probst, and A. Carraro, "Prevalence of primary and secondary exercise dependence and its correlation with drive for thinness in practitioners of different sports and physical activities," *International Journal of Mental Health and Addiction*, vol. 17, no. 1, pp. 89–101, 2019.

[66] X. Cheng, M. Song, J. Kong et al., "Influence of prolonged visual display terminal use and exercise on physical and mental conditions of internet staff in Hangzhou, China," *International Journal of Environmental Research and Public Health*, vol. 16, no. 10, p. 1829, 2019.

[67] J. L. Johnson, C. A. Slentz, L. M. Ross, K. M. Huffman, and W. E. Kraus, "Ten-year legacy effects of three eight-month exercise training programs on cardiometabolic health parameters," *Frontiers in Physiology*, vol. 10, no. 10, p. 452, 2019.

[68] J. Qiu, B. Shen, M. Zhao, Z. Wang, B. Xie, and Y. Xu, "A nationwide survey of psychological distress among Chinese people in the COVID-19 epidemic: implications and policy recommendations," *General Psychiatry*, vol. 33, no. 2, Article ID e100213, 2020.

[69] S. C. Hong, "Influence of physical activity on mental health of the elderly," *Sports Research Review*, vol. 78, pp. 153–157, 2005.

[70] J. F. Hair, R. E. Anderson, R. L. Tatham, and W. C. Black, *Multivariate Data Analysis*, Upper Saddle River, 1998.

[71] A. Ströhle, "Sports psychiatry: mental health and mental disorders in athletes and exercise treatment of mental disorders," *European Archives of Psychiatry and Clinical Neuroscience*, vol. 269, no. 5, pp. 485–498, 2019.

[72] D. Gursoy, C. Jurowski, and M. Uysal, "Resident attitudes," *Annals of Tourism Research*, vol. 29, no. 1, pp. 79–105, 2002.

[73] V. J. Janesick, "The choreography of qualitative research design: minuets,improvisations, and crystallization," in *Handbook of Qualitative Research*, N. K. Denzin and Y. S. Lincoln, Eds., pp. 379–399, Sage, California, CA, USA, 2000.

[74] Strauss & Corbin, *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*, Sage, Newbury Park, CA, USA, 1990.

Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 3723715, 13 pages
https://doi.org/10.1155/2021/3723715

Research Article

A Deep Learning Model of Dual-Stage License Plate Recognition Applicable to the Data Processing Industry

Chun-Liang Tung,[1] Ching-Hsin Wang ,[2] and Bo-Syuan Peng[1]

[1]*Department of Information Management, National Chin-Yi University of Technology, Taichung 411030, Taiwan*
[2]*Department of Leisure Industry, National Chin-Yi University of Technology, Taichung 411030, Taiwan*

Correspondence should be addressed to Ching-Hsin Wang; thomas_6701@yahoo.com.tw

Received 3 August 2021; Accepted 4 October 2021; Published 11 November 2021

Academic Editor: Kuei-Hu Chang

Automatic License Plate Recognition (ALPR) is a widely used technology. However, due to the influence of complex environmental factors, recognition accuracy and speed of license plate recognition have been challenged and expected. Aiming to construct a sufficiently robust license plate recognition model, this study adopted multitask learning in the license plate detection stage, used the convolutional neural networks of single-stage detection, RetinaFace, and MobileNet, as approaches to license plate location, and completed the license plate sampling through the calculation of license plate skew correction. In the license plate character recognition stage, the Convolutional Recurrent Neural Network (CRNN) integrated with the loss function of the CTC model was employed as a segmentation-free and highly robust method of license plate character recognition. In this study, after the license plate recognition model, DLPR, trained the PVLP dataset of vehicle images provided by company A in Taiwan's data processing industry, it performed tests on the PVLP dataset, indicating that its precision was 98.60%, recognition accuracy was 97.56%, and recognition speed was FPS > 21. In addition, according to the tests on the public AOLP dataset of Taiwan's vehicles, its recognition accuracy was 97.70% and recognition speed was FPS > 62. Therefore, not only can the DLPR model be applied to the license plate recognition of real-time image streams in the future, but also it can assist the data processing industry in enhancing the accuracy of license plate recognition in photos of traffic violations and the performance of traffic service operations.

1. Introduction

The research on Automatic License Plate Recognition (ALPR) has been done for more than 20 years [1]. ALPR technology has also made considerable progress and has been widely used in different application fields and industries, such as automatic traffic violation detection [2, 3]. Take Taiwan's traffic management, for example. After confirming the fact that the driving violation is committed, the traffic violation adjudication unit needs to issue a traffic ticket (containing a photo as proof of the violation) and send it to the driver to pay for the fine. Therefore, the data processing services industry can provide the police in charge of penalties with related services, such as assisting in printing and mailing traffic tickets. The processing procedure is as follows: first, obtain the data of traffic violation cases from various reporting units; next, submit the data to the filing center to import traffic violation photos and citations into the filing system and then to complete registration and monitoring after confirming the car registration information with the Motor Vehicles Office; last, pass the data on to the printing center to complete printing, postal delivery, and transferred mailing data packaging. While importing the traffic violation cases into the filing system, the filer can learn the car registration information, date, location, speed limit, driving speed, and so on from the photo and citation. Meanwhile, the filer must carefully confirm the data one by one and then import them. This process is all manually performed, which is not only cumbersome but also likely to cause business losses to the company when the imported data are incorrect and even lead to an increase in the police's workload. If the violation photos and violation citations can be analyzed by ALPR first, not only can it reduce the rate of filing error, but it also can speed up the operation process. Therefore, this study adopts the Dual-stage License Plate Recognition Model (DLPR) based on MobileNets, RetinaFace, CRNN, and CTC to enhance the license plate recognition rate and speed for the traffic violation photos and thereby assist the data processing industry in the license plate recognition accuracy of the traffic violation photos as well as the efficiency of the service operation.

With the successful development and application of deep learning in the field of computer vision, such as face recognition and detection, relevant advanced face recognition algorithms are also widely applied to the research of Automatic License Plate Recognition [4–8]. However, the license plate recognition technology still has many challenges in reality, such as the pixel level of the camera, the effects of light and shadow during the day and at night, different weather conditions, different shooting angles, and even possible reflections or stains on the license plates, all of which are complex variables so that the license plate recognition system is prone to recognition errors or failures. In particular, the recognition procedures employed by the license plate recognition technology in the past mostly adopted the three-stage recognition method: license plate detection, character segmentation, and character recognition; especially in the stage of character segmentation, license plate images in a more complex environment were often segmented imperfectly, resulting in incorrect character recognition. Wang [9] established the Chinese City Parking Dataset (CCPD), which contained 250,000 images of different vehicles in different environments, classified the images according to different environmental factors, and proposed a vehicle license plate recognition methodology called Multitask Convolutional Neural Network for license plate detection and recognition (MTLPR). MTLPR is based on the Multitask Convolutional Neural Network (MTCNN) [10] originally used in the face detection model and then applied to the license plate detection. Also, MTLPR collocates the Convolutional Recurrent Neural Network (CRNN) with the Connectionist Temporal Classification (CTC) to conduct training to carry out an optical character recognition without character segmentation [11, 12]. The research result shows that the license plate recognition in CCPD using MTLPR can reach the recognition accuracy of 98%.

Although the application of license plate recognition technology is relatively common, the improvement of accuracy is still limited. Taking the application of smart parking lot management as an example, its license plate recognition accuracy of more than 90% indicates its application value. Besides, the interface of the parking payment system allows users to confirm whether the license plate numbers and vehicle photos belong to their own vehicles or the license plate recognition system can perform a fuzzy comparison with the dataset for the currently recognized license plate number, so there is a certain error tolerance space, and the photo-taking environment of the parking lot can be controlled to a certain degree, in order to avoid the environmental factor that affects the recognition rate. However, when facing the issues of traffic law enforcement, any character of the license plate number recognized by ALPR cannot be wrong or missing, especially character "-" in Taiwan's license plate, whose position cannot be wrongly recognized. If the license plates of all vehicles cannot be correctly recognized, the workload of manual processing will increase. On the other hand, there is a variety of photo sources for traffic law enforcement based on science and technology. For example, photos of traffic violations are taken around the clock by the fixed cameras on the roadside outdoors. Consequently, they may be influenced by various complex environmental factors, such as weather change, different day and night light, light and shadow reflections, and distances between cameras and offending vehicles. Another example is the photo for proof taken by a roadside parking toll collector. This photo was taken by a toll collector with a mobile phone. Therefore, the position of the license plate in the photo was affected by environmental factors. Not only was it affected by light and shadow, but also it was affected by different shooting angles due to the field situation or personal operation, usually including high-angle shot, skew angle of the horizontal axis, horizontal offset, and bias angle of the vertical axis. Under the influence of the abovementioned various environmental factors, if the robustness of the license plate recognition method cannot be adopted, the recognition rate will often be unsatisfactory.

Every country has its own license plate encoding format or appearance arrangement, and the development of LPR needs to be adjusted based on different regions. Take the Taiwanese license plate regulated by the Directorate General of Highways of Taiwan, for example. The current vehicles in Taiwan have new-style license plates with 7 characters and old-style license plates with 6 characters, whereas special vehicles have 5- or 4-character license plates. In addition, even the font styles used on the new-style and old-style license plates are different as well. Moreover, based on application requirements, the "-" character on the license plate also needs to be correctly recognized. However, the "-" character is arranged in different positions of the new style, old style, and special vehicles, making it difficult to correctly identify the position of the "-" character on all license plates. Therefore, these special conditions have become one of the challenges of LPR.

The research purpose of this study is to propose a methodology of license plate recognition that can adapt to the influence of a variety of realistic environmental factors, reach a fairly high rate of precision and accuracy under the influence of various environmental factors after completing the test results of training the license plate recognition model, and enable the calculation speed to meet the requirements of real-time detection and recognition, leaving more room of development and application for the license plate recognition technology. In the experiment, this study adopts the Taiwanese public license plate dataset, Application-Oriented License Plate (AOLP) [13], and the Taiwanese license plate dataset of a company (the company has signed a confidentiality contract with the government), Private Vehicle License Plate (PVLP), in the Taiwan data service industry to perform training and testing of the DLPR license plate detection and recognition model proposed by this study. However, due to legal issues, the PVLP dataset is a nonpublic database, so it is only applied to this study, whereas the AOLP dataset is a public database, so it can be provided for external use and academic research.

2. Related Works

If the early artificial neural network (ANN) needs to extract features from images to perform object detection and recognition, it must rely on the artificially defined feature descriptor or the so-called feature extractor. For example, Haar-like features [14] are used for object detection; features of histograms of oriented gradients (HOG) [15] are used for pedestrian detection; local binary patterns (LBP) [16] are used to calculate the texture characteristics of objects. However, these artificially defined feature descriptors are usually combined with machine learning algorithms, such as support vector machines (SVM) [17] and adaptive boosting (AdaBoost) [18], to effectively classify or predict eigenvalues. Lecun et al. [19] were the first scholars who proposed the concept of convolutional neural network (CNN). Also, they came up with gradient-based neural network learning and applied it to document recognition [20, 21]. The computation of CNN usually goes through multiple convolutional layers and pooling layers, respectively, and finally enters the fully connected layers to analyze the classification results of eigenvalues.

Nevertheless, the development of CNN was not quite smooth at the beginning. The reasons were the limitations of hardware technology in the 1990s and the CNN training's heavy reliance on a large number of sample datasets, but the concept of the establishment of large sample datasets was not very popular at that time. Later, GPU (Graphics Processing Unit) developed by Nvidia was born, which can help accelerate massive matrix computations of CNN. Krizhevsky et al. improved CNN and proposed AlexNet [22], combining GPU to perform high-speed training and inference computation [23–25]. AlexNet beat other methodologies in the object recognition contest of ImageNet 2012 and won the championship, which made many scholars' eyes widen at the sight. This is also a milestone in the entire field of machine learning. Since then, CNN and deep learning have gradually become today's significant studies. Nowadays, CNN is widely used in image recognition [26] and natural language processing [27]; for example, Tao et al. [8, 9] adopted a lightweight CNN as a network structure for license plate character recognition. Its main task is to perform feature extraction on data and carry out parameter learning through a large amount of data. It can adaptively adjust the weight parameters of the feature extractor and then extract more meaningful information from the data. Compared with the traditional artificially defined feature descriptors, CNN has better robustness, and the recognition rate in many studies using CNN is better than that in the traditional recognition methodologies. The reason is as mentioned by Zhao et al. [28]. If the features of the object extracted from the image adopt the artificially defined feature descriptor, it will be difficult to cover the factors that need to be resolved, such as light, shadow, and complex background. Therefore, as long as a large and diverse number of samples can be provided in the CNN training phase, a better feature extractor can be obtained after the training is completed.

The loss functions of the object detection models that adopt deep learning will directly affect the identification capability of the models. Among them, the loss functions more commonly used in the regression model include MSE (Mean Square Error) and MAE (Mean Absolute Error), the loss function more commonly used in the classification model includes cross entropy, and the loss functions more commonly used in the CNN model include Huber Loss, Focal Loss, and Center Loss. The advantage of Huber Loss is that MSE is less sensitive to outliers and able to accelerate the speed of convergence. In the well-known deep learning object detection models, RetinaNet [29] uses Focal Loss to deal with the foreground-background class imbalance or data imbalance in object detection; YOLOv4 [30] adopts BCE (Binary Cross Entropy) as the loss function of classification and MSE as the loss function of coordinate; SSD [31] employs cross entropy as the loss function of the predicted boundary box and class prediction.

Object detection algorithms using deep learning algorithms can be divided into three categories: sliding-window algorithm, two-stage detectors, and one-stage detectors [29]. The sliding-window algorithm is one of the early methodologies. LeCun et al. integrated the sliding-window algorithm with the CNN model to detect and recognize handwritten digits from the background [32]. Astawa et al. [33] adopted the sliding-window algorithm as a method of license plate location and performed license plate detection using photos taken by mobile phones with a detection rate of 94%. In their paper, the sliding-window algorithm was used to capture multiple candidate regions in the photos, HOG was employed by each candidate region to calculate an eigenvalue, and finally, SVM was applied to judge whether the eigenvalue was a license plate. Uijlings et al. [34] used two-stage detectors and a selective search algorithm to perform license plate detection. First, in the first stage called the proposal stage, a large number of candidate regions with more possibilities were proposed; although these regions still contained foregrounds and backgrounds, they also had excluded a large number of background regions at the same time. In the second stage, the detection model was employed to determine these candidate regions; if they were foregrounds, their categories would be identified; if they were backgrounds, they would be eliminated. The method of two-stage detectors is obviously more efficient than the sliding-window algorithm to detect all regions. R-CNN (Region Convolution Neural Network) [35] also applies the method of two-stage detectors to object detection. In the first stage, a selective search algorithm is adopted; in the second stage, the CNN model performs the classification task. As a result, it significantly improves the recognition accuracy. Faster R-CNN [36] merges the first-stage Region Proposal Networks (RPN) with the second-stage CNN, which not only greatly reduces a large number of meaningless candidate regions (alternative regions) but also enhances accuracy and facilitates training so that there is no need to train these two network models separately. Compared with the two-stage detectors, one-stage detectors lack the proposal stage, so they require more object candidate regions for processing, and they also need to deal with the problem of the imbalance of foreground and background data like SSD [31, 37], YOLOv4 [30], RetinaNet [29], and RetinaFace [38] do. Based on the above description, this study adopts a one-stage detector as the algorithm for license plate location in order to achieve the purpose of real-time license plate location.

The development of the convolutional neural network (CNN) has become more and more mature and has been widely used [39, 40]. Therefore, the Dual-stage License Plate Recognition Model (DLPR) proposed by this study also adopts the CNN-based methodology in the license plate location stage and the license plate character recognition stage. The license plate location stage refers to the methodology of RetinaFace applied to human face detection, which is a one-stage object detector of multitasking learning. Since its architecture has an excellent effect on the application to face detection, this study applies the architecture of the RetinaFace framework and MobileNet to the license plate location stage. In the license plate character recognition stage, to help the character recognition technology adapt to the complex shooting environment, this study adopts an end-to-end segmentation-free method of license plate character recognition; that is, the CRNN model is integrated with the CTC loss function for optical character recognition.

3. Methods

The DLPR license plate recognition method proposed by this study aims to maintain high and robust recognition ability under the influence of a variety of real environments. The overall architecture of the license plate recognition system is displayed in Figure 1.

In the architecture of the DLPR license plate recognition system, the license plate location module regards RetinaFace as the basis for the license plate location. RetinaFace is a multitask neural network infrastructure. This model is used to perform tasks such as license plate detection, bounding box regression, and landmark regression. Therefore, after the location of the license plate and the coordinates of its four key points (upper left, lower left, upper right, and lower right) are predicted, these four key points can correct the license plate placed at a skew angle via perspective transformation, and then a screenshot of the corrected license plate can be received. Subsequently, the screenshot of the license plate is input into the license plate character recognition module, which is a segmentation-free character recognition method implemented by CRNN combining CTC, and finally, the license plate string can be recognized.

RetinaFace can accurately predict the location of the license plate and the coordinates of four key points on the license plate in the image frame. Accordingly, this network infrastructure includes the outputs of three tasks-a classification task, a bounding box regression task, and a landmark regression task. This study adopted the faster MobileNet [41] as the backbone network of the model and combined the Feature Pyramid Network (FPN) [42] to keep scale-invariant as much as possible. In FPN, the feature maps of each layer $P = \{p_1, p_2, p_3\}$ are input to the context module, and three different sizes of receptive fields are applied to the feature maps of each layer for the convolution operation to obtain the feature maps at different scales in order to further maintain the scale-invariant ability. Finally, the context module calculates the feature maps of each layer and then performs three multitask calculations again, including classification head, bounding box head, and landmark head. Besides, the prior box mechanism proposed by SSD is used as an encoding and decoding mechanism during model training and inference; that is, this is a method utilizing bounding box head and landmark head to figure out the feature maps corresponding to the coordinates of the original image.

3.1. MobileNet and Feature Pyramid Network. MobileNet is a lightweight convolutional neural network that employs the calculation method of Depthwise Separable Convolution to achieve the effect of reducing the computation load without affecting the size of the output structure. This study used MobileNet as the backbone network infrastructure combining the Feature Pyramid Network (FPN) to maintain the model's scale-invariant ability, which means that the model targeted at any objects of any scales has a certain degree of robustness which can predict their positions as well as sizes. FPN divides the backbone network into several sequential stages. In this study, there were three layers in the FPN so that $C = \{c_1, c_2, c_3\}$ represented the feature maps of each stage in the backbone network. The topmost feature map c_3 had deeper dimensional features and more meaningful semantics, but it could not accurately correspond to the coordinate of the original image where the object was located; on the contrary, the bottom feature map c_1 had a lower dimensionality, which could not acquire better semantic information, but it was closer to the original image in dimension so that it was easier to correspond to the coordinate of the original image. The establishment of the feature pyramid started with the top-layer feature map $c_3 = p_3$, and p_3 performed upsampling to make itself the same size with c_2; c_2 processed by the (1×1) convolution was added up to obtain the second feature pyramid layer p_2. Based on the above mentioned, a three-layer feature pyramid, $P = \{p_1, p_2, p_3\}$, was established, so FPN retained the feature map information of the low and high layers to achieve the scale-invariant ability.

3.2. Context Module. The application of the context module originated from the face detection method proposed by SSH [43]. This method can detect faces with different scales for the same input image at one time. The context module uses receptive fields in different sizes to generate different feature maps and finally concatenates them into a new feature map, which also achieves a certain degree of scale invariance. This study input three feature maps of $P = \{p_1, p_2, p_3\}$ obtained from the FPN calculation into their corresponding context module for calculation. The context module was composed of

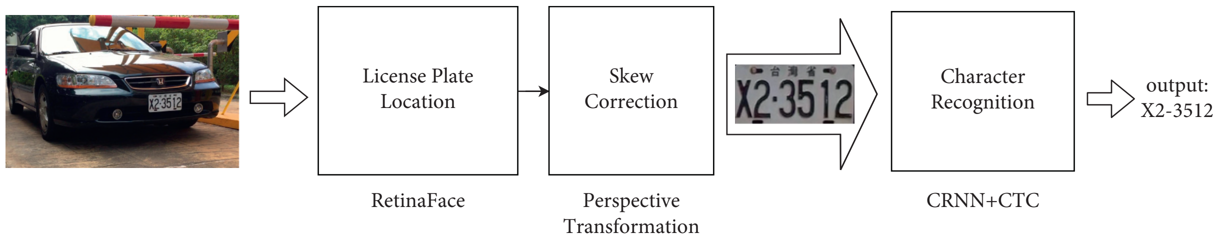


Figure 1: Architecture of DLPR license plate recognition model.

three groups of receptive fields in various sizes, whose convolution kernel sizes were, respectively, presented as $\{(3 \times 3), (5 \times 5), (7 \times 7)\}$. Lastly, the feature maps obtained by convolutions of these three groups of convolution kernels were merged into a new feature map, $\text{FM} = \{fm_1, fm_2, fm_3\}$.

3.3. Prior Box. The prior box mechanism used by SSD can be applied to the model training and inference of one-stage detectors. The purpose of this mechanism is to set up a prior box with a fixed number and fixed size. The prior box is set up according to the anchor on the final feature map, regarded as the basis for the feature map and its corresponding coordinate of the original image. Therefore, this study used the three feature maps of $\text{FM} = \{fm_1, fm_2, fm_3\}$ calculated by the context module to set an anchor for the center position of each cell in the two-dimensional tensor of each feature map and set up two prior boxes with each anchor viewed as the center. In other words, each anchor on the feature map was the center point of the prior box, and its coordinates on the original image were expressed as $(X_{\text{pbox}}, Y_{\text{pbox}})$, $X_{\text{pbox}} \leftarrow (X_{fm_i} + 0.5) \times s_{fm_i}$, and $Y_{\text{pbox}} \leftarrow (Y_{fm_i} + 0.5) \times s_{fm_i}$, in which (X_{fm_i}, X_{fm_i}) indicated all coordinates in the two-dimensional tensor of the feature map fm_i, 0.5 was the offset of the coordinates, and s_{fm_i} was the stride of the layer. For each feature map of $\text{FM} = \{fm_1, fm_2, fm_3\}$, the two prior boxes set up on the anchors had different sizes. The prior boxes on fm_1 were matrix $fm_1^1 B_{\text{pbox}} = [bij] \in R^{16\times16}$of (16×16) and matrix $fm_1^2 B_{\text{pbox}} = [bij] \in R^{32\times32}$ of(32×32); the prior boxes on fm_2 were matrix $fm_2^1 B_{\text{pbox}} = [bij] \in R^{64\times64}$of (64×64) and matrix $fm_2^2 B_{\text{pbox}} = [bij] \in R^{128\times128}$ of (128×128); and the prior boxes on fm_3 were matrix $fm_3^1 B_{\text{pbox}} = [bij] \in R^{256\times256}$ of (256×256) and matrix $fm_3^2 B_{\text{pbox}} = [bij] \in R^{512\times512}$ of (512×512). Since the size of the original input image varies, the shape and size of the feature map FM calculated by the context module will be different as well. Therefore, the total number of the set prior boxes is N_{pbox}, whose calculation is shown in equation (1), where $\text{num}_{\text{pbox}} = 2$ represents that the number of prior boxes on each anchor is set to 2 in this study.

$$N_{\text{pbox}} = \sum_i \text{num}_{\text{pbox}} \times h_{fm_i} \times w_{fm_i}, \quad i = 1, 2, 3. \tag{1}$$

Targeted at numerous prior boxes, a matching mechanism combining the prior box and the ground-truth box is adopted in the training phase as a matching method for the positive and negative samples of the prior boxes. By calculating the Intersection over Union (IoU) between the ground truth B_{gt} and the prior box B_{pbox}, the IoU value is used as the basis of matching. Its calculation is displayed as follows:

$$J\left(B_{gt}, B_{\text{pbox}}\right) = \frac{\left|B_{gt} \cap B_{\text{pbox}}\right|}{\left|B_{gt} \cup B_{\text{pbox}}\right|}, \tag{2}$$

where the value of output by function $J(B_{gt}, B_{\text{pbox}})$ is $\text{IoU} > 0.5$, indicating that B_{pbox} will be matched as the positive sample of B_{gt}; otherwise, B_{pbox} will be matched as the negative sample of B_{gt}.

3.4. Multitask Loss Function. In the final multitask calculation stage, for the feature maps of $\text{FM} = \{fm_1, fm_2, fm_3\}$, three multitask network calculations are performed, respectively, which are classification head representing the classification task, bounding box head for the bounding box regression task, and landmark head for the landmark regression task [8, 9]. Each head analyzes all the prior boxes on FM according to the purposes of the tasks, and then the final outputs $\{A_{\text{cls}}, A_{b\,\text{box}}, A_{\text{landmark}}\}$ of the model are obtained. Among the outputs, the output of the classification head, $A_{\text{cls}} = [a_{ij}] \in R^{N_{\text{pbox}}\times2}$, represents the confidence score of the j^{th} category of the i^{th} prior box in the classification task; the output of the bounding box head, $A_{b\,\text{box}} = [a_{ij}] \in R^{N_{\text{pbox}}\times4}$, represents the offset of the j^{th} coordinate value of the i^{th} prior box in the bounding box regression task; the output of the landmark head, $A_{\text{landmark}} = [a_{ij}] \in R^{N_{\text{pbox}}\times8}$, represents the offset of the j^{th} coordinate value of the i^{th} prior box in the landmark regression task. In order to train the model to accurately perform these three tasks, this study adopted a multitask learning method. In the case of weights shared by the model, the loss function of the classification task $L^{\text{cls}}(x_n, y_n)$, the loss function of the bounding box regression task $L^{b\,\text{box}}(x_n, y_n)$, and the loss function of the landmark regression $L^{\text{landmark}}(x_n, y_n)$ are defined, respectively. The target function of the overall model training is demonstrated in the following equation:

$$\theta^* = \arg\min_{\theta}\left[\frac{1}{N_{\text{samples}}}\sum_{n=1}^{N_{\text{samples}}}\left(\alpha_{\text{cls}}L_n^{\text{cls}} + \alpha_{b\,\text{box}}L_n^{b\,\text{box}} + \alpha_{\text{landmark}}L_n^{\text{landmark}}\right)\right], \tag{3}$$

where the neural network parameter θ is adjusted to minimize the overall loss value and N_{samples} represents the total number of training samples. Also, this study set parameters $\{\alpha_{\text{cls}} = 1, \alpha_{b\,\text{box}} = 2, \alpha_{\text{landmark}} = 1\}$ as the weights of training all tasks. The purpose of training the classification task in this study is to accurately distinguish whether each prior box is a license plate, that is, to perform two types of binary classification. The output of the classification head, $A_{\text{cls}} = [a_{ij}] \in R^{N_{pbox}\times 2}$, means that each prior box contains two confidence scores for judging whether it is a license plate, so they can also be called classification probabilities. The classification task uses cross entropy as the basis to design the loss function of its task, $L^{\text{cls}}(x_n, y_n)$, whose definition is exhibited in the following equation:

$$L^{\text{cls}}(x_n, y_n) = L_n^{\text{cls}} = \frac{1}{N_{pbox}}\sum_{i=1}^{N_{pbox}} -y_i^{\text{cls}}\log(p_i) + \left(1 - y_i^{\text{cls}}\right)(1 - \log(p_i)), \tag{4}$$

where there are N_{pbox} prior boxes in the n^{th} image sample. After the prior boxes N_{pbox} match all the ground truths of y_n on the image, each prior box will be matched to its corresponding ground truth. As to $y_i^{\text{cls}} \in \{0, 1\}$, 0 represents that the i^{th} prior box is matched as a nonlicense plate, 1 represents a license plate, and p_i represents the probability that the i^{th} prior box is predicated as a license plate. Therefore, cross entropy calculates the difference between y_i^{cls} and p_i and retrieves their average to solve for the loss function of the n^{th} sample.

In this study, the bounding box regression task was trained so that the model could accurately calculate the offset between the specific prior box and the ground-truth box. The output of the bounding box head, $A_{b\,\text{box}} = [a_{ij}] \in R^{N_{pbox}\times 4}$, indicates that each prior box contains the offsets of four coordinate values, which are the offsets of the upper left corner coordinates, width, and height $(\Delta x_i, \Delta y_i, \Delta w_i, \Delta h_i)$. The bounding box regression task uses L_2 distance as the basis to design the loss function $L^{b\,\text{box}}(x_n, y_n)$ of the task, as shown in the following equation:

$$L^{b\,\text{box}}(x_n, y_n) = L_n^{b\,\text{box}} = \frac{1}{N_{pbox}}\sum_{i\,\in\,\text{Positive}}^{N_{pbox}} \left\| y_i^{b\,\text{box}} - o_i^{b\,\text{box}} \right\|_2^2. \tag{5}$$

Among all the prior boxes of the n^{th} sample x_n, only the prior boxes that are matched as positive samples are considered to calculate the L_2 distance between the true offset $y_i^{b\,\text{box}}$ and the offset $o_i^{b\,\text{box}}$ predicted by the model, whose average is retrieved to solve for the loss function of the n^{th} sample.

Since the landmark regression task was trained in this study, the model could accurately calculate the offsets between the upper left corner coordinates of the specific prior box and the 4 ground landmarks on the real object. The output of landmark head, $A_{\text{landmark}} = [a_{ij}] \in R^{N_{pbox}\times 8}$, means that each prior box contains the offsets of the coordinates (upper left, lower left, upper right, and lower right) of 4 ground landmarks, that is, a total of 8 offset values $\{\Delta p_1 x_i, \Delta p_1 y_i, \Delta p_2 x_i, \Delta p_2 y_i, \Delta p_3 x_i, \Delta p_3 y_i, \Delta p_4 x_i, \Delta p_4 y_i\}$. Similarly, the landmark regression task also adopts the L2 distance as the basis to design the loss function of its task, $L^{\text{landmark}}(x_n, y_n)$, as displayed in the following equation:

$$L^{\text{landmark}}(x_n, y_n) = L_n^{\text{landmark}} = \sum_{i\,\in\,\text{Positive}}^{N_{pbox}} \left\| y_i^{\text{landmark}} - o_i^{\text{landmark}} \right\|_2^2. \tag{6}$$

Among all the prior boxes of the n^{th} sample x_n, only the prior boxes that are matched as positive samples are considered to calculate the L_2 distance between the true offset y_i^{landmark} and the offset o_i^{landmark} predicted by the model, whose average is retrieved to solve for the loss function of the n^{th} sample.

3.5. Perspective Transformation. In the process of photographing license plates, the license plates may be skewed and difficult to be accurately recognized due to the different shooting angles. Therefore, this study adopted the method of MTLPR, performing perspective transformation with four corner points of the license plate. The license plate with a skewed angle on the image was projected to more positive new coordinates to correct its skew. Perspective transformation is adopted to help the two-dimensional plane $\begin{bmatrix} u & v & 1 \end{bmatrix}$ correspond to the three-dimensional space $\begin{bmatrix} x & y & z \end{bmatrix}$ through the transformation matrix, $M = [a_{ij}] \in R^{3\times 3}$, as shown in the following equation:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}\begin{bmatrix} u \\ v \\ 1 \end{bmatrix}, \tag{7}$$

where (u, v) refers to the coordinates on the original image and (x, y, z) represents the coordinates in the transmitted three-dimensional space. To make the transmitted three-dimensional space be seen as a two-dimensional plane, the three-dimensional space $\begin{bmatrix} x & y & z \end{bmatrix}$ is divided by z to form a new three-dimensional space $\begin{bmatrix} x' & y' & 1 \end{bmatrix}$. Consequently, (x', y') can be regarded as new coordinates on the two-dimensional plane, as displayed in the following equation:

$$x' = \frac{x}{z} = \frac{a_{11}u + a_{12}v + a_{13}}{a_{31}u + a_{32}v + a_{33}} = \frac{k_{11}u + k_{12}v + k_{13}}{k_{31}u + k_{32}v + 1},$$
$$y' = \frac{y}{z} = \frac{a_{21}u + a_{22}v + a_{23}}{a_{31}u + a_{32}v + a_{33}} = \frac{k_{21}u + k_{22}v + k_{23}}{k_{31}u + k_{32}v + 1}, \tag{8}$$

where $k_{ij} = (a_{ij}/a_{33})$. Thus, k_{ij} has 8 elements in total, and 4 sets of coordinates on the original image and the corresponding coordinates of each set on the new plane are needed to solve for k_{ij} and further solve for the transmission matrix $M = [a_{ij}] \in R^{3\times3}$. Therefore, the coordinates of the four key points of the license plate on the image predicted in the license plate location stage are $P_1 = (p_1x, p_1y)$, $P_2 = (p_2x, p_2y)$, $P_3 = (p_3x, p_3y)$, and $P_4 = (p_4x, p_4y)$, representing the coordinates of the upper left corner, lower left corner, upper right corner, and lower right corner of the license plate. Also, the coordinates of these four key points and their corrected coordinates on the new plane, $P_1' = (0, 0)$, $P_2' = (0, \max(p_2y, p_4y))$, $P_3' = (\max(p_3x, p_4x), 0)$, and $P_4' = (\max(p_3x, p_4x), \max(p_2y, p_4y))$, are substituted into equation (8) to solve for the transmission matrix $M = [a_{ij}] \in R^{3\times3}$. Then, all the points in the quadrilateral surrounded by P_1, P_2, P_3, and P_4 on the original image can correspond to the new plane to complete the license plate correction.

3.6. License Plate Character Recognition of CRNN and the CTC Loss Function. The license plate character recognition in this study adopts the Convolutional Recurrent Neural Network (CRNN) as an infrastructure and CTC as the loss function to train the model, and finally, the result sequence predicted by the model is transcribed into the license plate number, as shown in Figure 2. First, the license plate image is standardized and compressed into size (100×32) and input into the CNN layer for feature extraction to obtain a feature map. Subsequently, the feature map is converted into a feature sequence, and then the feature sequence is input into the RNN layer for analysis and prediction to receive an output sequence. Finally, the output sequence is transcribed into a license plate string.

CRNN is composed of the Convolution Neural Network layer (CNN layer) and the Recurrent Neural Network layer (RNN layer) in order. In this study, the feature map $(16 \times 1 \times 512)$ calculated by the CNN layer is mapped into a feature sequence X of $(512 \times 1 \times 16)$ with a sequence length of 16; the input of each time step is a 512-dimensional feature vector, as shown in Figure 3. As a result, the feature sequence can be input into the RNN layer for calculation.

The RNN layer performs the classification task of 36 characters (from A to Z, and 0 to 9); that is, 36-dimensional classification result y_t is received after feature vector x_t at each time step is analyzed. When 512-dimensional x_t enters the input layer, W_1 is the weight of the first hidden layer, which is a matrix of order $(N_1 \times 512)$; in addition, b_1 is the bias of the first hidden layer, and the output result of the first hidden layer, H_1, is calculated by equation (9) as follows:

$$H_1 = \mathrm{ACT}(W_1 \cdot x_t + b_1), \tag{9}$$

$$y_t = \mathrm{ACT}(W_{\mathrm{output}} \cdot H_n + b_{\mathrm{output}}), \tag{10}$$

where H_1 is obtained by means of x_t calculated with weight W_1, bias b_1, and activation function ACT. H_1 is a vector of dimension N_1 and can be subsequently used as the input of the second hidden layer. After H_1 is calculated by the second hidden layer, H_2 as a vector of dimension N_2 is received and continuously regarded as the input of the next layer. The above process continues until the output layer is figured out. Similarly, the output of the last hidden layer H_n is also used as the input of the output layer. Through the calculation of weight W_{output}, bias b_{output}, and activation function ACT, y_t is obtained as a 36-dimensional classification result, as displayed in equation (10), where $W_{\mathrm{output}} \in R^{36\times N_n}$ is a matrix of $(36 \times N_n)$. The single-layer architecture of LSTM can sequentially input the feature sequence $X = \{x_1, x_2, x_3, \ldots, x_{16}\}$ beginning from x_1, perform calculations to obtain the output result y_1, and transfer memory and output to the next time step. Based on this rule, circular calculations are performed until x_{16}. Finally, the result sequence $Y = \{y_1, y_2, y_3, \ldots, y_{16}\}$ is obtained.

This study adopted the Deep LSTM network with a hidden layer depth of 256 layers. Each layer of LSTM needs to train 4 sets of weights and biases, so there are $256 \times 4 \times 2$ sets of parameters. h_t^d is expressed as the output of the d^{th} hidden layer at time step t; c_t^d is expressed as the memory of the d^{th} hidden layer at time step t. In the Deep LSTM calculation, the output of each layer, h_t^d, will be used as the input of the next layer, and h_t^d and c_t^d will also be passed to the next time step. Finally, the output of the last layer, h_t^{255}, is equal to the result y_t output at time step t. In the training and inference process of LSTM, this study used the CTC alignment to train the best parameter $\overset{*}{\theta}$, as shown in equation (11), where S is the license plate characters used for training and $P(S|Y) = \sum P(h|Y)$:

$$\theta^* = \arg\max_{\theta} P_\theta(S|Y). \tag{11}$$

After the inference calculation of Deep LSTM, the result sequence $Y = \{y_1, y_2, y_3, \ldots, y_{16}\}$ is obtained. The purpose of the task is to analyze the probabilities of various character classes at each time step from the feature sequence. Therefore, y_t is a 36-dimensional vector, representing the classification result of 36 classes. This study transmitted the result at each time step into a probability distribution of 36 classes via the softmax function so that the result sequence Y could be viewed as the probability distribution of 36-character classes at each time step.

Finally, in CRNN's transcription layer, this study utilized the result sequence Y to find the best path L^* and output license plate characters by means of greedy decode. The greedy decode only considers the node with the highest probability as the path; therefore, although h^* can only approximate the result of the best path L^*, it can save more computing resources and achieve the effect of rapid recognition.

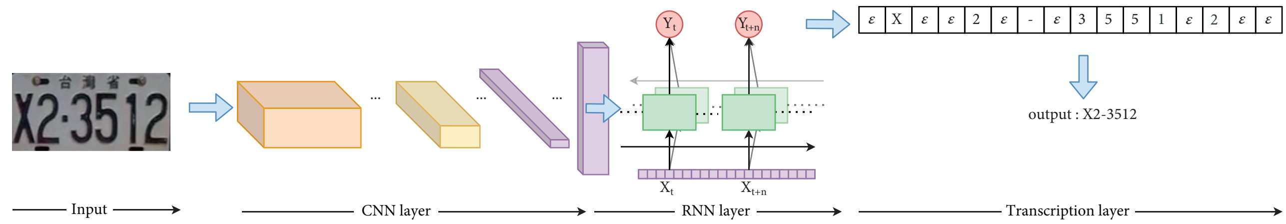


Figure 2: CRNN + CTC license plate character recognition procedure.

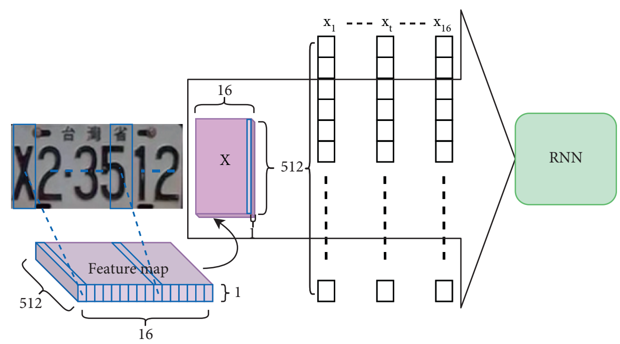
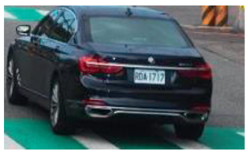


Figure 3: The feature map corresponding to the feature sequence.

4. Experiments

4.1. Dataset. This study used Taiwan's Application-Oriented License Plate (AOLP) dataset released by the National Taiwan University of Science and Technology with a total of 2049 sample photos and the Private Vehicle License Plate (PVLP) dataset of company A with a total of 25,707 sample photos as the training samples and test samples of the DLPR model proposed by this study. The AOLP dataset collected Taiwanese license plate images in a variety of real environments according to some specific criteria, while the PVLP dataset directly collected Taiwanese license plate images applied to different scenarios in the real world, such as highways, expressways, and roadside parking spaces. In the AOLP dataset, according to the criteria of image shooting, the dataset was divided into three different subdatasets, including Access Control (AC), Traffic Law Enforcement (LE), and Road Patrol (RP). AC had a total of 681 photos, consisting of 374 photos with image resolution 320 × 240 and 307 photos with image resolution 352 × 240, in which all the license plates had 6 characters. LE had a total of 757 photos, consisting of 582 photos with image resolution 640 × 480 and 175 photos with image resolution 320 × 240, in which there were 756 photos of six-character license plates and only one photo of seven-character license plates. RP had a total of 611 photos with image resolution 320 × 240, in which all the license plates had 6 characters. In the AC subdataset, the image was taken from the entrance or gate control, so the vehicle was basically driving at a low speed or completely stopped, and the camera was mounted within 5 meters from the vehicle; in the LE subdataset, the image source was from the offending vehicle taken by the fixed speed camera on the roadside, and the environment of the road vehicle image was relatively complicated; in the RP subdataset, the image was taken by a handheld camera or a camera mounted on a moving vehicle so that the vehicle image was shot at a random angle and distance. The AOLP license plate photo samples are shown in Table 1. In the PVLP dataset, there were many types of license plate photos, such as images taken by fixed speed cameras, images of roadside vehicles taken manually, and black-and-white photos taken by speed cameras on freeways. Therefore, these license plate photos contained a variety of real environmental factors, such as weather changes, day and night lights, light and shadow reflection, distances of photographing vehicles, image pixels, image quality, and different shooting angles, making PVLP license plate samples quite abundant and diverse. Besides, images taken by fixed speed cameras also included multiple types of vehicles, such as automobiles, locomotives, heavy locomotives, and large vehicles. The PVLP dataset included the subdataset of Fixed Speed Camera Image (FC) with image resolution 1337 × 977 and a total of 11,576 photos, comprising 27 images of four-character license plates, 71 images of five-character license plates, 4047 images of six-character license plates, and 7431 images of seven-character license plates, the subdataset of Taiwan Highway Shot Image (TS) with image resolution 1392 × 1040 and a total of 11,060 photos, comprising 300 images of five-character license plates, 4208 images of six-character license plates, and 6552 images of seven-character license plates, and the subdataset of Roadside Shot Image (RS) with image resolution 614 × 460 and a total of 3071 photos, comprising 4 images of five-character license plates, 1209 images of six-character license plates, and 1858 images of seven-character license plates. The PVLP photo samples are shown in Table 1.

Table 1: Samples of AOLP and PVLP in different types of datasets.

Dataset	AC	LE	RP
AOLP			
	FC	TS	RS
PVLP			

4.2. Training for License Plate Location and Recognition. The training of the DLPR license plate recognition model was to utilize PVLP data to perform a series of model training, such as license plate location and license plate character recognition, using a total of 25,707 image samples containing vehicles and license plates. In the training of the license plate location model, this study input these 25,707 image samples into the license plate location model for training with a total of 250 epochs, set 32 image samples each time to perform training iterations 804 times in each epoch of training, and set the initial learning rate as 0.3. During the training process, the value of classification loss is 4.858 in the initial epoch and converges to 0.469 in the final epoch; the value of bounding box regression loss is 4.342 in the initial epoch and converges to 0.234 in the final epoch; the value of landmark regression loss is 22.24 in the initial epoch and converges to 0.795 in the final epoch, as shown in Figure 4(a). In the training of the license plate character recognition model, this study utilized the trained license plate location model to locate and correct the license plates for the 25,707 samples of PVLP. After the model located the license plates and calculated their correct locations, those samples with IoU values greater than 0.5 would be selected as the samples of license plate character recognition. Therefore, a total of 25,218 license plate snapshot images were collected from PVLP and viewed as training and validation samples for the license plate character recognition model. This study divided the 25,218 license plate snapshot images into two parts: train set and validation set, in a ratio of 7 : 3. In the data analysis of machine learning, 70% of the samples are used for training, and 30% of the samples are used for verification and testing. The accuracy is approximately between 4-fold and 5-fold cross validation. Also, according to Nguyen et al. [44], the research results have revealed that the ratio of 70/30 used for training and testing datasets can provide the proposed models with the best training and verification effect. Although 10-fold cross validation can provide better accuracy, the data ratio of 70/30 is still used for training, verification, and testing because of the complexity of the model in this study. The train set could be regarded as the parameter training of the model. The validation set was viewed as a phased verification for the training result of each epoch, examining the model training result of the current epoch for the fitting ability of the validation set. Furthermore, the fitting ability was used as the judgment of the convergence condition. The training of the license plate character model had a total of 1851 epochs. In each epoch of training, 128 image samples were set each time to perform training iterations 198 times. The initial learning rate was set to 0.1. In the training process, the CTC loss value is 0.274 in the initial epoch, and the model ability is significantly improved when it approaches 200 epochs, in which the loss value is 0.0283; the CTC loss value is 0.0275 when the model finally converges. In the validation process, the CTC loss value is 0.116 in the initial epoch, the loss value is $6.46e-3$ when approaching 200 epochs, and the CTC loss value is $5.92e-3$ when the model finally converges, as shown in Figure 4(b). At this time, this model can achieve a recognition accuracy of 99.00% for the license plate character recognition of the validation set after calculation.

4.3. Model Performance Evaluation with AOLP and PVLP Datasets. In order to evaluate the DLPR's capability of license plate location, this study conducted an evaluation of the detection model by calculating precision, recall, and receiver operator characteristic curve (ROC curve). Precision can be used to evaluate how correctly the license plate location model determines the location of the license plate. The higher the precision is, the more accurate the detection model is for determining the location of the license plate. Recall can be used to evaluate how correctly the license plate location model finds the location of the license plate. The higher the recall is, the better the ability of the detection model is for finding the location of the license plate. Receiver operator characteristic curve (ROC) and area under the curve (AUC) can be used to assess whether the license plate location model has sufficient capability to discriminate license plates. Generally speaking, it is presumed that the model has a certain ability of judgment as the values of AUC are greater than 0.5. The experimental results show that the license plate location model in this study uses 25,707 license

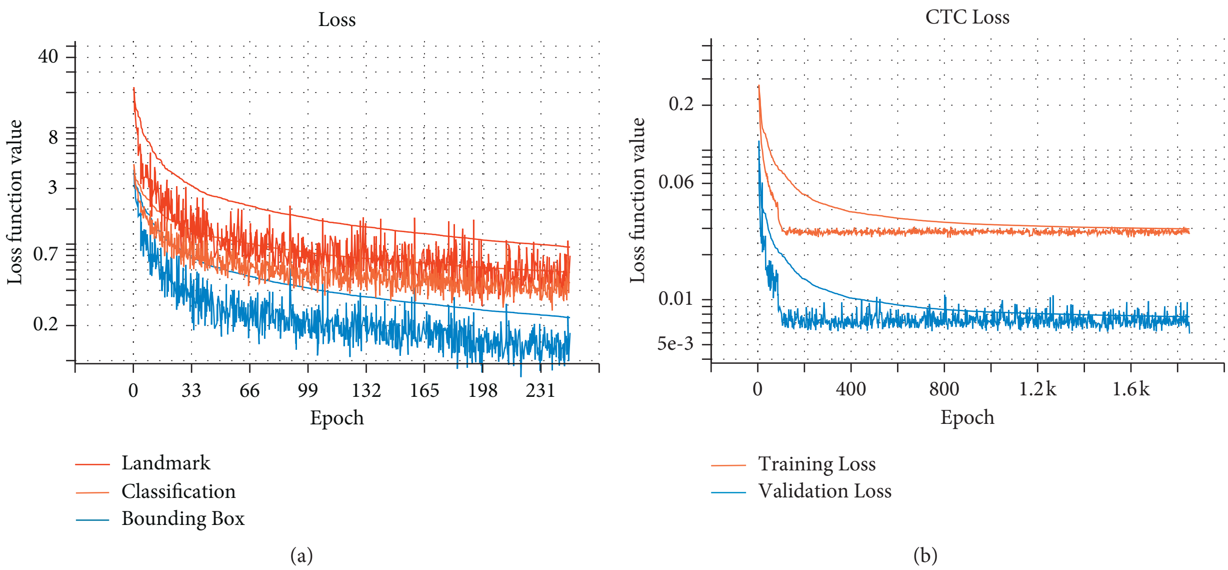


Figure 4: Loss function values of DLPR during the training of license plate location.

plate image samples from the PVLP dataset for the license plate location tests; under the conditions of confidence score threshold = 0.9 and IoU threshold > 0.5, the precision of the license plate location tests is 0.9860 and the recall is 0.9810. Also, 2049 license plate image samples from the AOLP dataset are used for the license plate location tests; under the conditions of confidence score threshold = 0.9 and IoU threshold > 0.5, the precision of the license plate location test is 0.8402 and the recall is 0.8549. Compared with the precision and recall of the PVLP dataset for testing, the precision and recall of AOLP drop significantly. The reason is that PVLP and AOLP have a slight difference in labeled locations of the bounding box of the license plate. Therefore, after the IoU threshold > 0.4 is revised, the experiment is conducted. Then, the precision of the license plate location tests increases to 0.9592, and the recall also rises to 0.9760, as shown in Table 2. In the experiment of measuring DLPR's ability to differentiate between license plates, the ROC curve is displayed in Figure 5, where AUC = 0.98 as the PVLP dataset is used for testing and AUC = 0.94 as the AOLP dataset is used for testing, indicating that they both have good capabilities of discriminating license plates.

In the part of verifying the accuracy of the DLPR license plate character recognition model, the measurement standard is that as long as all the license plate number characters and word sequences on the license plate snapshot images are recognized correctly without redundant characters, the recognition is considered correct; otherwise, it is seen as an error. The accuracy of the license plate character recognition also depends on the license plate location ability of the recognition model as well as the stability of the license plate skew correction. Therefore, when testing the license plate character recognition, this study only selected the license plate snapshot images of IoU > 0.5 between the bounding box predicted by the model and the ground-truth bounding box as samples of verifying the accuracy of the license plate character recognition model. The experimental results are demonstrated in Table 3. DLPR has a very good recognition level for the captured images of the license plates as long as the license plate location is accurate enough, that is, IoU > 0.5, and the "-" character among the license plate characters can also be correctly recognized. However, in the AOLP dataset, the labeled content of the license plate does not contain the "-" character. Therefore, this study removed the "-" character from the predicted license plate characters and then compared it with the labeled content of the license plate provided by AOLP. The results show that all the recognitions can be completely correct under the condition of IoU > 0.5. Conversely, in the tests of the PVLP dataset, the "-" character is taken into consideration. After the labeled content of the license plate provided by PVLP is compared, the average of accuracy can reach 99.88%.

Considering the accuracy of the complete license plate recognition, DLPR needs to go through the complete computational process, including license plate location, license plate skew correction, and license plate character recognition, to figure out the license plate number. After the number is compared with the labeled content of the license plate, the accuracy of license plate recognition can be calculated. In addition, the frame per second (FPS) is used to measure the speed of license plate recognition. The higher the FPS value is, the faster the calculation speed of recognition is. According to the experimental results, as shown in Table 4, when the PVLP dataset is applied to the license plate location and license plate recognition, the average of accuracy is 97.56%, and the speed of recognition is FPS > 21. However, as to the license plate sample of RS, the recognition rate is only 94.06% since the environmental conditions of shooting on mobile phones are more complicated. Overall, the DLPR license plate recognition model proposed by this study has been equipped with the ability of real-time license plate recognition in real environments. In consequence, it has a variety of values of practical applications, such as its capability of helping the data processing industry

Table 2: Precision and recall of license plate location tests with different threshold (TH).

Dataset	Confidence score TH	IoU TH	Precision	Recall
PVLP	0.9	>0.5	0.9860	0.9810
AOLP	0.9	>0.5	0.8402	0.8549
AOLP	0.9	>0.4	0.9592	0.9760

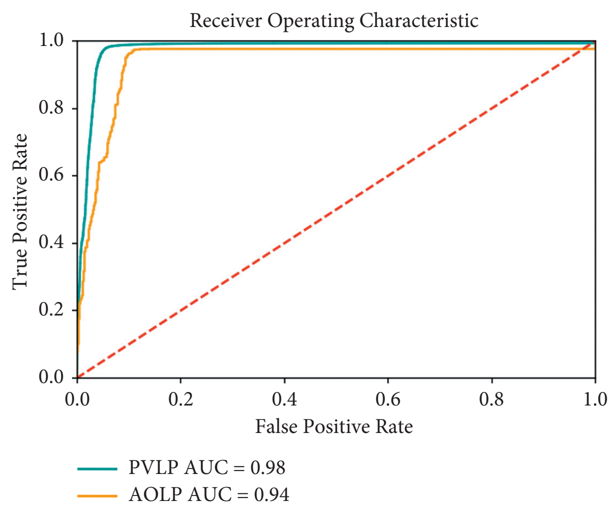


Figure 5: ROC curve of DLPR license plate location model.

Table 3: Accuracy (ACC) measurement of license plate character recognition to the proposed model with AOLP and PVLP dataset.

IoU threshold	AOLP AC Number	AOLP AC ACC (%)	AOLP LP Number	AOLP LP ACC (%)	AOLP RP Number	AOLP RP ACC (%)	PVLP Number	PVLP ACC (%)
0.5 < IoU < 0.75	476	100	455	100	291	100	2637	99.92
0.75 < IoU < 0.9	38	100	158	100	247	100	12024	99.83
0.9 < IoU	0	*X*	30	100	14	100	10558	99.91

Table 4: Average accuracy (Avg. ACC) and speed (FPS) of DLPR using the PVLP dataset for license plate recognition.

Method	PVLP FC (%)	PVLP TS (%)	PVLP RS (%)	Avg. ACC (%)	FPS
DLPR	99.19	99.43	94.06	97.56	>21

Table 5: Average accuracy (Avg. ACC) and speed (FPS) of DLPR using the AOLP dataset for license plate recognition.

Method	AOLP AC (%)	AOLP LE (%)	AOLP RP (%)	Avg. ACC (%)	FPS
Li et al. [40]	94.85	94.19	88.38	92.47	0.66
Li et al. [41]	95.59	96.43	83.80	91.94	2.5
Björklund et al. [42]	94.60	97.80	96.90	96.43	39.21
DLPR (proposed)	96.91	98.01	98.20	97.70	62.93

enhance the accuracy of license plate recognition in photos of traffic violations as well as the performance of traffic service operations.

DLPR uses the AOLP dataset to conduct a thorough experiment on license plate location and recognition and compares it with its related research, as shown in Table 5. The experimental results show that the accuracy of DLPR recognition performs the best in the categories of AC, LE, and RP. The license plate recognition method proposed by scholars Li et al. [45, 46] merged license plate location and character recognition into the same major neural network. Its license plate character recognition phase is similar to the architecture applied in this study, which is based on the end-to-end segmentation-free character recognition method. Accordingly, it has good performances in datasets of AC and LE, whereas it has a poor performance in the RP dataset since the license plate skew correction is not adopted. The framework of license plate recognition proposed by Björklund et al. [47] included the processing of license plate skew correction. In the character recognition stage, the character recognition based on the segmentation method was adopted. Therefore, in the tests of the AOLP dataset, its performance of accuracy was good. As to the DLPR framework proposed by this study, it has a stable and accurate prediction performance for its capabilities of license plate location and license plate skew correction. Also, it is integrated with CRNN's segmentation-free character recognition method to achieve the best recognition accuracy in the tests of the AOLP dataset. Additionally, under the condition of image resolution 640 × 640, the speed of license plate recognition can reach 62.93 FPS.

5. Conclusions

In terms of research contribution, after the Dual-stage License Plate Recognition Model (DLPR) proposed by this study used the PVLP dataset provided by company A in Taiwan's data processing industry to train license plate location and license plate character recognition, the final accuracy of license plate recognition could reach 97.56% in the PVLP dataset, and FPS > 21. Besides, this study also performed tests on the AOLP dataset and compared it with its related research; the results indicated that the license plate accuracy for all of the AOLP subdatasets gathered in the DLPR model was the best, with an average of 97.70%, and FPS could reach 62.93. Consequently, the DLPR model can be applied to the license plate recognition of the real-time image stream in the future and assist Taiwan's data processing industry in improving not only the accuracy of license plate recognition in photos of traffic violations but also the performance of traffic service operations. In this study, DLPR adopted three major processes: license plate location, skew correction, and character recognition. In particular, the character recognition applied an end-to-end segmentation-free character recognition method based on CRNN, having good recognition accuracy for the precisely located and skew-corrected license plate snapshot images. Therefore, when it was practically applied to the license plate recognition using cellphone cameras, it could correctly recognize license plate characters from the license plate images with different angles.

Still, there is a research limitation in this study. This study used the undisclosed PVLP dataset to train the license plate recognition model as well as the AOLP dataset to test the license plate recognition model. In the AOLP dataset, a team was established to record and classify license plates in various real environments according to specific criteria, and these detailed parameters were sufficient enough to allow the license plate recognition model to improve its ability of license plate recognition in some specific environments. Nonetheless, the current PVLP dataset cannot provide detailed parameters related to the license plate samples, and it can only provide three subdatasets for the preliminary classification. Hence, the establishment of a license plate dataset with detailed classification parameters will be of great help to the study of license plate recognition. Future research on this field will help the PVLP dataset construct a complete record of license plate parameters and focus on the study of license plate recognition in more complex environments.

Data Availability

Data are available upon request to the authors. The data source is obtained from the questionnaire analysis of the author's research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] J. Shashirangana, H. Padmasiri, D. Meedeniya, and C. Perera, "Automated license plate recognition: a survey on methods and techniques," *IEEE Access*, vol. 9, pp. 11203–11225, 2021.

[2] H. Chandra, Michael, K. R. Hadisaputra, H. Santoso, and E. Anggadjaja, "Smart parking management system: an integration of RFID, ALPR, and WSN," in *Proceedings of the 3rd International Conference on Engineering Technologies and Social Sciences (ICETSS)*, pp. 1–6, Bangkok, Thailand, August 2017.

[3] P. Agarwal, K. Chopra, M. Kashif, and V. Kumari, "Implementing ALPR for detection of traffic violations: a step towards sustainability," *Procedia Computer Science*, vol. 132, pp. 738–743, 2018.

[4] J. Liu, Y. Feng, and H. Wang, "Facial expression recognition using pose-guided face alignment and discriminative features based on deep learning," *IEEE Access*, vol. 9, pp. 69267–69277, 2021.

[5] D. Gonzalez Dondo, J. A. Redolfi, R. G. Araguas, and D. Garcia, "Application of deep-learning methods to real time face mask detection," *IEEE Latin America Transactions*, vol. 19, no. 6, pp. 994–1001, 2021.

[6] O. Bulan, V. Kozitsky, P. Ramesh, and M. Shreve, "Segmentation- and annotation-free license plate recognition with deep localization and failure identification," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 9, pp. 2351–2363, 2017.

[7] X. Tao, F. Gu, and S. Xie, "The network design of license plate recognition based on the convolutional neural network," in *Proceedings of the 11th International Symposium on Artificial Intelligence Algorithms and Applications*, pp. 749–758, Guangzhou, China, November 2019.

[8] X. Tao, L. Li, and L. Lu, "A lightweight convolutional neural network for license plate character recognition," *Artificial Intelligence Algorithms and Applications*, vol. 1205, pp. 379–387, 2019.

[9] W. Wang, J. Yang, M. Chen, and P. Wang, "A light CNN for end-to-end car license plates detection and recognition," *IEEE Access*, vol. 7, pp. 173875–173883, 2019.

[10] K. Zhang, Z. Zhang, Z. Li, and Y. Qiao, "Joint face detection and alignment using multitask cascaded convolutional networks," *IEEE Signal Processing Letters*, vol. 23, no. 10, pp. 1499–1503, 2016.

[11] A. Graves, S. Fernandez, F. Gomez, and J. Schmidhuber, "Connectionist temporal classification: labelling unsegmented sequence data with recurrent neural networks," in *Proceedings of the 23rd International Conference on Machine Learning*, pp. 369–376, Pittsburgh, PA, USA, July 2006.

[12] B. Shi, X. Bai, and C. Yao, "An end-to-end trainable neural network for image-based sequence recognition and its application to scene text recognition," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 39, no. 11, pp. 2298–2304, 2017.

[13] G.-S. Hsu, J.-C. Chen, and Y.-Z. Chung, "Application-oriented license plate recognition," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 2, pp. 552–561, 2013.

[14] C. P. Papageorgiou, M. Oren, and T. Poggio, "A general framework for object detection," in *Proceedings of the 6th*

International Conference on Computer Vision (IEEE Cat. No.98CH36271), pp. 555–562, Bombay, India, 1998.

[15] N. Dalal and B. Triggs, “Histograms of oriented gradients for human detection,” in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, vol. 1, pp. 886–893, Honolulu, HI, USA, July 2005.

[16] T. Ojala, M. Pietikainen, and T. Maenpaa, “Multiresolution gray-scale and rotation invariant texture classification with local binary patterns,” *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 24, no. 7, pp. 971–987, 2002.

[17] C. Cortes and V. Vapnik, “Support-vector networks,” *Machine Learning*, vol. 20, no. 3, pp. 273–297, 1995.

[18] Y. Freund and R. E. Schapire, “A decision-theoretic generalization of on-line learning and an application to boosting,” *Journal of Computer and System Sciences*, vol. 55, no. 1, pp. 119–139, 1997.

[19] Y. LeCun, B. Boser, J. S. Denker et al., “Backpropagation applied to handwritten zip code recognition,” *Neural Computation*, vol. 1, no. 4, pp. 541–551, 1989.

[20] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, *Learning Internal Representations by Error Propagation*, California Univ. San Diego La Jolla Inst for Cognitive Science, San Diego, CA, USA, 1985.

[21] Y. Lecun, L. Bottou, Y. Bengio, and P. Haffner, “Gradient-based learning applied to document recognition,” *Proceedings of the IEEE*, vol. 86, no. 11, pp. 2278–2324, 1998.

[22] A. Krizhevsky, I. Sutskever, and G. E. Hinton, “ImageNet classification with deep convolutional neural networks,” *Communications of the ACM*, vol. 60, no. 6, pp. 84–90, 2017.

[23] C. H. Wang, “An intuitionistic fuzzy set-based hybrid approach to the innovative design evaluation mode for green products,” *Advances in Mechanical Engineering*, vol. 8, pp. 1–16, 2016.

[24] K.-P. Lin, H.-F. Chang, T.-L. Chen, Y.-M. Lu, and C.-H. Wang, “Intuitionistic fuzzy C-regression by using least squares support vector regression,” *Expert Systems with Applications*, vol. 64, pp. 296–304, 2016.

[25] L.-L. Li, J. Sun, C.-H. Wang, Y.-T. Zhou, and K.-P. Lin, “Enhanced Gaussian process mixture model for short-term electric load forecasting,” *Information Sciences*, vol. 477, pp. 386–398, 2019.

[26] K. Wang and M. Z. Liu, “Object recognition at night scene based on DCGAN and faster R-CNN,” *IEEE Access*, vol. 8, pp. 193168–193182, 2020.

[27] X. Zhou, Y. Li, and W. Liang, “CNN-RNN based intelligent recommendation for online medical pre-diagnosis support,” *IEEE/ACM Transactions on Computational Biology and Bioinformatics*, vol. 18, no. 3, pp. 912–921, 2021.

[28] Z.-Q. Zhao, P. Zheng, S.-T. Xu, and X. Wu, “Object detection with deep learning: a review,” *IEEE Transactions on Neural Networks and Learning Systems*, vol. 30, no. 11, pp. 3212–3232, 2019.

[29] T. Y. Lin, P. Goyal, R. Girshick, K. He, and P. Dollar, “Focal loss for dense object detection,” in *Proceedings of the 2017 IEEE International Conference on Computer Vision (ICCV)*, pp. 2980–2988, Venice, Italy, October 2017.

[30] C. Y. Wang, A. Bochkovskiy, and H. Y. M. Liao, “Scaled-YOLOv4: scaling cross stage partial network,” in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 13029–13038, Nashville, TN, USA, 2021.

[31] W. Liu, D. Anguelov, D. Erhan et al., “SSD: single shot MultiBox detector,” in *Proceedings of the European Conference on Computer Vision*, pp. 21–37, Amsterdam, The Netherlands, October 2016.

[32] R. Vaillant, C. Monrocq, and Y. Le Cun, “Original approach for the localisation of objects in images,” *IEE Proceedings-Vision, Image, and Signal Processing*, vol. 141, no. 4, pp. 245–250, 1994.

[33] I. Astawa, I. Caturbawa, I. Sajayasa, and I. M. Atmaja, “Detection of license plate using sliding window, histogram of oriented gradient, and support vector machines method,” *Journal of Physics: Conference Series*, vol. 953, Article ID 12062, 2018.

[34] J. R. R. Uijlings, K. E. A. van de Sande, T. Gevers, and A. W. M. Smeulders, “Selective search for object recognition,” *International Journal of Computer Vision*, vol. 104, no. 2, pp. 154–171, 2013.

[35] R. Girshick, J. Donahue, T. Darrell, and J. Malik, “Rich feature hierarchies for accurate object detection and semantic segmentation,” in *Proceedings of the 2014 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pp. 580–587, Columbus, OH, USA, June 2014.

[36] S. Ren, K. He, R. Girshick, and J. Sun, “Faster R-CNN: towards real-time object detection with region proposal networks,” *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 39, no. 6, pp. 1137–1149, 2017.

[37] C. Y. Fu, W. Liu, A. Ranga, A. Tyagi, and A. C. Berg, *DSSD: Deconvolutional Single Shot Detector*, https://arxiv.org/abs/1701.06659, 2017.

[38] J. Deng, J. Guo, Y. Zhou, J. Yu, I. Kotsia, and S. Zafeiriou, *RetinaFace: Single-Stage Dense Face Localisation in the Wild*, https://arxiv.org/abs/1905.00641, 2019.

[39] L. Zhao, Q. Li, C. H. Wang, and Y. C. Liao, “3D brain tumor image segmentation integrating cascaded anisotropic fully convolutional neural network and hybrid level set method,” *Journal of Imaging Science and Technology*, vol. 64, Article ID 040411, 2020.

[40] K. Bai, Q. Li, and C. H. Wang, “Integrating improved U-Net continuous maximum flow algorithm for 3D brain tumor image segmentation,” *Journal of Imaging Science and Technology*, vol. 64, Article ID 040412, 2020.

[41] A. G. Howard, *Mobilenets: Efficient Convolutional Neural Networks for Mobile Vision Applications*, https://arxiv.org/abs/1704.04861, 2017.

[42] T. Lin, P. Dollár, R. Girshick, K. He, B. Hariharan, and S. Belongie, “Feature pyramid networks for object detection,” in *Proceedings of the 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pp. 936–944, Honolulu, HI, USA, July 2017.

[43] M. Najibi, P. Samangouei, R. Chellappa, and L. S. Davis, “SSH: Single stage headless face detector,” in *Proceedings of the IEEE International Conference on Computer Vision (ICCV)*, pp. 4885–4894, Venice, Italy, October 2017.

[44] Q. H. Nguyen, H. B. Ly, L. S. Ho et al., “Influence of data splitting on performance of machine learning models in prediction of shear strength of soil,” *Mathematical Problems in Engineering*, vol. 2021, Article ID 4832864, 2021.

[45] H. Li, P. Wang, M. You, and C. Shen, “Reading car license plates using deep neural networks,” *Image and Vision Computing*, vol. 72, pp. 14–23, 2018.

[46] H. Li, P. Wang, and C. Shen, “Toward end-to-end car license plate detection and recognition with deep neural networks,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 3, pp. 1126–1136, 2019.

[47] T. Björklund, A. Fiandrotti, M. Annarumma, G. Francini, and E. Magli, “Robust license plate recognition using neural networks trained on synthetic images,” *Pattern Recognition*, vol. 93, no. 1, pp. 134–146, 2019.

Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 4325708, 10 pages
https://doi.org/10.1155/2021/4325708

Research Article

An Adaptive Location-Based Tracking Algorithm Using Wireless Sensor Network for Smart Factory Environment

Po-Chih Chiu [1,2] **Kuo-Wei Su** [3] **Tsung-Yin Ou** [4] **Chih-Lung Yu** [2]
Chen-Yang Cheng [5] **Wei-Chieh Hsiao**,[6] **Ming-Hung Shu** [2,7] **and Guan-Yu Lin** [8]

[1]*College of Management, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan*
[2]*Department of Industrial Engineering and Management, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan*
[3]*Department of Information Management, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan*
[4]*Department of Marketing and Distribution Management, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan*
[5]*Department of Industrial Engineering and Management, National Taipei University of Technology, Taipei, Taiwan*
[6]*Department of Industrial Engineering and Enterprise Information, Tunghai University, Taichung, Taiwan*
[7]*Department of Healthcare Administration and Medical Informatics, Kaohsiung Medical University, Kaohsiung, Taiwan*
[8]*College of Management, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan*

Correspondence should be addressed to Chih-Lung Yu; i109143101@nkust.edu.tw

Received 13 July 2021; Revised 27 August 2021; Accepted 17 September 2021; Published 18 October 2021

Academic Editor: Kuei-Hu Chang

In recent years, how to improve the performance of smart factories and reduce the cost of operation has been the focus of industry attention. This study proposes a new type of location-based service (LBS) to improve the accuracy of location information delivered by self-propelled robots. Traditional localization algorithms based on signal strength cannot produce accurate localization results because of the multipath effect. This study proposes a localization algorithm that combines the Kalman filter (KF) and the adaptive-network-based fuzzy inference system (ANFIS). Specifically, the KF was adopted to eliminate noise during the signal transmission process. Through the learning of the ANFIS, the environment parameter suitable for the target was generated, to overcome the deficiency of traditional localization algorithms that cannot obtain real signal strength. In this study, an experiment was conducted in a real environment to compare the proposed localization algorithm with other commonly used algorithms. The experimental results show that the proposed localization algorithm produces minimal errors and stable localization results.

1. Introduction

Through the development of artificial intelligence, the maintenance and repair of machines in smart factories are different from the old way. There are already smart factories that use mechanical vibration and noise detection or environmental data to improve the reliability of equipment or knives [1–4]. However, installing sensors for detection in all the equipment would increase the cost significantly. This time, self-propelled robots can be used for inspection, effectively reducing the related costs. Of course, location-based service technology is very important at this point because it can effectively provide accurate equipment information. Location-based services (LBSs) have been widely applied in warehouse management, transportation, personnel tracking, and medical care [5, 6].

Currently, the commonly used location-based systems can be divided into indoor and outdoor systems [7]. In particular, although the global positioning system (GPS) is the most frequently used outdoor location-based system, it cannot be effectively used in an indoor environment because of the shading effect of buildings. Therefore, other techniques, such as radio frequency identification, wireless local area network, Bluetooth, and ZigBee, are required for indoor localization [8]. All of these techniques involve transmitting radio wave signals to establish a wireless sensor network for positioning. However, during the transmission process, signals may be influenced by the multipath effect; therefore, information received by the reader may be distorted, influencing the accuracy and stability of localization [9–11].

The interference in signal transmission is not entirely caused by obstacles; signal transmission may be interfered with by signals emitted from other electronic devices [12]. In addition, various receivers may experience different levels of interference because of varying transmission directions, despite using the same signal transmitter. Therefore, the result of positioning is influenced by obstacles in an environment, signals from other electronic devices, and the direction of signal transmission [13].

To solve the problems produced by varying transmission directions and the multipath effect caused by obstacles, this study proposed a localization algorithm by combining the Kalman filter (KF) to enhance the accuracy and stability of localization. The proposed algorithm was subsequently compared with existing localization algorithms.

This study has proposed an adaptive tracking system. Section 2 discusses related literature, the concepts of the location algorithm, Kalman filter, and adaptive-network-based fuzzy inference system (ANFIS). Section 3 illustrates the proposed algorithm for the smart factory. Section 4 details the demonstration of the experimental operations and examines the algorithm in the smart factory environment. Finally, Section 5 includes the conclusion and highlights follow-up research.

2. Related Work

Among the propagation path loss models, the most widely used models are the free-space propagation, log-distance path loss, and Hata models. In the free-space propagation model, the Friis free-space model is typically adopted. When the distance between a transmitter and receiver is given, the model can be used to calculate the average received power of the receiver as follows [14]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{1}$$

where P_t represents the transmission power of the transmitter; λ is the wavelength of the electromagnetic wave; L denotes the system dissipation coefficient; and G_t and G_r are the antenna gains for the transmitter and receiver, respectively. The calculation of antenna gains is related to the effective aperture (A_e):

$$G = \frac{4\pi A_e}{\lambda^2}. \tag{2}$$

The effective aperture is related to the antenna design. Therefore, when the transmitter and receiver use different antennas, despite using the same transmission power, the power received by the receiver may differ.

In equation (1), when the distance between the transmitter and receiver is 0 ($d = 0$), the received power cannot be determined. Therefore, a close-in distance (d_0) is defined in the model, and the received power in this condition is a reference power. Thus, the Friis free-space model can be expressed as (3):

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L}\left(\frac{d_0}{d}\right)^2 = P_r(d_0)\left(\frac{d_0}{d}\right)^2. \tag{3}$$

2.1. Kalman Filter. The KF is a well-known tool used to eliminate noise and can provide an efficient calculation approach for estimating system states [15,16]. By applying a series of regression models, the efficiency of the least-square method can be enhanced [17]. Because the internal state of a system cannot consistently be directly estimated, the KF has two primary assumptions: (1) the system is linear, and (2) the system error distribution and initial estimate probability distribution are both Gaussian distributions [16]. The KF applies the linear stochastic difference equation to construct prediction and measurement models, as expressed in equations (4) and (5):

$$x_{k+1} = Ax_k + Bu_k + w_k, \tag{4}$$

$$z_k = Hx_k + v_k, \tag{5}$$

where x_k indicates the state of a system at time k, A represents the conversion model for the system state, B denotes the control model for the control factor u_k, z_k is the observation state of a system at time k, and H is an observation model. In addition, w_k and v_k are system noise and observation noise, respectively, which are assumed to be mutually independent and to follow Gaussian distribution. w_k and v_k are expressed as equations (6) and (7):

$$w_k \sim N(0, Q), \tag{6}$$

$$v_k \sim N(0, R). \tag{7}$$

The calculation of the KF is a regression process that involves two steps, namely, prediction and correction. At the prediction step, the system state ($\hat{x}_{k-1}$) at time k-1 is used to calculate the a priori state of the system ($\hat{x}_k^-$) at time k.

$$\begin{aligned} \hat{x}_k^- &= A\hat{x}_{k-1} + Bu_{k-1}, \\ P_k^- &= AP_{k-1}A^T + Q. \end{aligned} \tag{8}$$

At the correction step, the observation value of the system at time k is used to adjust the system state at time k.

$$\begin{aligned} K_k &= P_k^- H^T \left(HP_k^- H^T + R\right)^{-1}, \\ \hat{x}_k &= \hat{x}_k^- + K_k\left(z_k - H\hat{x}_k^-\right), \\ P_k &= \left(I - K_k H\right)P_k^-, \end{aligned} \tag{9}$$

where P_k^- is the a priori estimation error of the system at time k, p_k is the estimation error of the system at time k, and K_k indicates the Kalman gain of the system at time k. In the KF, the Kalman gain is applied to adjust the state estimates;

therefore, the estimation errors of the systems can converge over time.

Other KF-related studies include that of Yim et al., who used KNN to find the distance between the target and the antenna and gave different weights to the EKF depending on whether the target was located at a corner or not [15].

2.2. Adaptive-Network-Based Fuzzy Inference System. The ANFIS has the characteristic of neural network learning and the advantage of the rules of a fuzzy inference system and can thus process nonlinear and complex systems and identify system rules. Figure 1 shows the framework of the ANFIS, which consists of five layers. The layers that comprise squares involve parameters, among which an optimal parameter can be obtained in each layer through learning adjustment. No parameters are involved in the layers comprising circles. The layers are explained as follows.

2.2.1. Layer 1: Input Layer

$$O_l^1 = \mu_{A_i}(x), \tag{10}$$

where x is the input of A, and A_i is the i^{th} semantic tag for input A. $\mu_{Ai}(x)$ is the membership function (MF) for the i^{th} semantic tag of input A. The bell-shaped distribution is the most frequently used MF that has values within the range of 0 to 1, as shown in (11):

$$\mu_{A_i}(x) = \frac{1}{1 + (x - c_i/a_i)^{2b_i}}, \tag{11}$$

where a_i, b_i, and c_i are parameters of the MF.

2.2.2. Layer 2: Rule Layer. The firing strength of the fuzzy rules is calculated using equation (12):

$$O_i^2 = w_i = \mu_{A_i}(x) \times \mu_{B_i}(y), \quad i = 1, 2. \tag{12}$$

2.2.3. Layer 3: Normalization Layer

$$O_i^3 = \overline{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1, 2. \tag{13}$$

2.2.4. Layer 4: Inference Layer. The output of the normalization layer is multiplied by the fuzzy rules to calculate the result of each rule.

$$O_i^4 = \overline{w}_i f_i = \overline{w}_i (p_i x + q_i y + r_i), \tag{14}$$

where f_i is the i^{th} rule, and p_i, q_i, and r_i are parameters for the i^{th} rule.

2.2.5. Layer 5: Output Layer. The weighted average of the results of the inference layer is computed to be the output of the ANFIS.

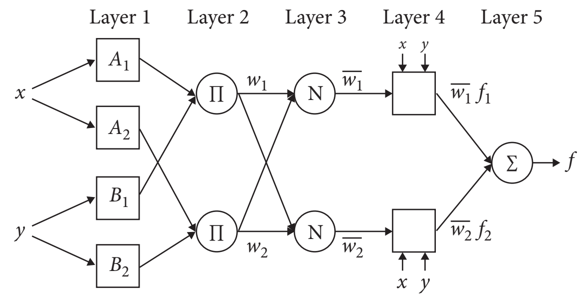


Figure 1: The framework of ANFIS [18].

$$O_i^5 = \sum \overline{w}_i f_i = \frac{\sum w_i f_i}{\sum w_i}. \tag{15}$$

The parameters in each layer of the ANFIS are adjusted using a hybrid learning algorithm. When the optimal parameter adjustment is achieved, the calculation efficiency of the system and the output accuracy can be improved. Related studies using ANFIS include the following: Oliveira et al. combined signal strength and Link Quality Indication (LQI) to calculate distance and then used a fuzzy inference system to find the target location [19]; Lee et al. applied the parameters considered in the computational process to a fuzzy inference system to generate a new filter, which was then combined with a prototype filter to find the location of the target [20]; and other related practical applications of the relevant literature [21, 22].

3. Methods

3.1. Localization Algorithm Combining the Kalman Filter and Adaptive-Network-Based Fuzzy Inference System. The proposed localization algorithm assumed that the relationship between RSSI and distance remains the same in the same environment with the same distance. In addition, the concept of reference tag was used to identify the environment parameters suitable for the targeted object. The algorithm comprises four steps, as shown in Figure 2. The following section describes Figure 2. For more information, please refer to the descriptions on pages 7–11.

First, considering the use of antennas to receive the signal of the reference tag and the object to be measured, the signal will be distorted by the influence of multipath during the transmission process. Therefore, this study uses the characteristics of the Kalman filter (KF) to eliminate the noise during the transmission of the signal, so that the received signal is clean. The KF was then integrated with the modified Friis free-space model to identify the relationship between signals and distance. Through the correction learning of the ANFIS, the environment parameter suitable for the target was yielded, which was then combined with the modified WCG to determine the location of the target.

3.1.1. Kalman Filter. The KF can filter noise caused by interference in signal transmission; therefore, readers can receive clean signals emitted by reference tags and the target without interference. Because all of the reference tags and

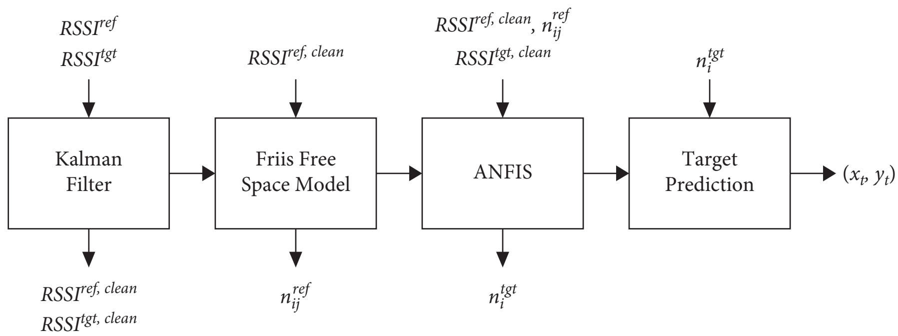


Figure 2: The framework of the proposed localization algorithm.

targets used in this study were static, their states would not change during the system conversion from the true state to the observation state, except for being interfered with by noise. Therefore, the prediction and measurement models of the KF were simplified as equations (16) and (17):

$$s_{k+1} = s_k + w_k, \tag{16}$$

$$z_k = x_k + v_k, \tag{17}$$

where

$$\begin{gathered} s_k = \left[\text{RSSI}_k^{\text{ref}} \ \ \text{RSSI}_k^{\text{tgt}} \right]^T, \\ w_k \sim N(0, Q), \end{gathered} \tag{18}$$

where S_k is the true state of the system at time k, $\text{RSSI}_k^{\text{ref}}$ represents the signal strength of a reference tag at time k, $\text{RSSI}_k^{\text{tgt}}$ signifies the signal strength of the target at time k, w_k indicates the noise in the true state of the system at time k, and Q is the variance of the true system state. However, because the variation of the system's true state cannot be obtained easily, Q is typically excluded from the consideration.

$$\begin{gathered} z_k = \left[\text{RSSI}_k^{\text{ref,measure}} \ \ \text{RSSI}_k^{\text{tgt,measure}} \right]^T, \\ v_k \sim N(0, R), \end{gathered} \tag{19}$$

where Z_k is the observation state of the system at time k; $\text{RSSI}_k^{\text{ref,measure}}$ is the observed signal of a reference tag at time k; $\text{RSSI}_k^{\text{tgt,measure}}$ represents the observed signal of a target at time k; v_k indicates the noise in the observation state of the system at time k; and R denotes the variance of the observation state.

The observation state of the system was used to predict the estimate of the true state of the system, and the correction was performed to reduce errors in the estimate and the actual value. The initial estimate ($\hat{s}_0$) and error (P_0) were given, and iteration calculation was performed, as shown in equations (20)–(24):

$$\hat{s}_k = \hat{s}_{k-1}, \tag{20}$$

$$P_k^- = P_{k-1}, \tag{21}$$

$$K_k = P_k^- \left(P_k^- + R\right)^{-1}, \tag{22}$$

$$\hat{s}_k = \hat{s}_k^- + K_k \left(z_k - \hat{s}_k^-\right), \tag{23}$$

$$P_k = \left(I - K_k\right) P_k^-, \tag{24}$$

where $\widehat{s_k^-}$ is the a priori true state estimate of the system at time k, $\widehat{s_k^-}$ is the true state estimate of the system at time k, P_k^- signifies the a priori estimation error of the system at time k, P_k indicates the estimation error of the system at time k, and K_k is the Kalman gain of the system at time k.

3.1.2. Friis Free-Space Model. The Friis free-space model is the propagation path loss model obtained in a free space based on the inverse square law, which assumes that RSSI is inversely square proportional to distance (RSSI $\propto$ $1/d^2$). However, the real environment is subject to the influence of the multipath effect; in other words, the signals received by readers frequently interfere. Therefore, the relationship between signal values and distance is not inversely square proportional. Thus, the Friis free-space model was modified to be

$$\text{RSSI} = \text{RSSI}_{\widehat{d_0}} \left(\frac{d_{\widehat{d_0}}}{d} \right)^n, \tag{25}$$

where $\text{RSSI}_{\widehat{d_0}}$ and $d_{\widehat{d_0}}$ are $P_r(d_0)$ and d_0 in equation (25); and n is the environment parameter, which varies according to the change in environment and distance.

Moreover, when the environment and distance between the transmitter and receiver are the same, the receiver signal strength is influenced by various levels of interference in signal transmission, causing changes in the value of n. Thus, this study employed reference tags to determine the possible value of n in the environment. The approach is as follows:

Assume that I readers ($i = 1, 2, \ldots, I$) and J reference tags ($j = 1, 2, \ldots, J$) were deployed in an indoor environment for localization. The value of n was calculated as follows:

$$\begin{aligned}
\mathrm{RSSI}_{ij}^{\mathrm{ref,clean}} &= \mathrm{RSSI}_{\mathrm{close}}\left(\frac{d_{\mathrm{close}}}{d_{ij}}\right)^{n_{ij}^{\mathrm{ref}}},\\
&\Rightarrow \frac{\mathrm{RSSI}_{ij}^{\mathrm{ref,clean}}}{\mathrm{RSSI}_{\mathrm{close}}} = \left(\frac{d_{\mathrm{close}}}{d_{ij}}\right)^{n_{ij}^{\mathrm{ref}}},\\
&\Rightarrow \log\left(\frac{\mathrm{RSSI}_{ij}^{\mathrm{ref,clean}}}{\mathrm{RSSI}_{\mathrm{close}}}\right) = n_{ij}^{\mathrm{ref}}\log\left(\frac{d_{\mathrm{close}}}{d_{ij}}\right),\\
&\Rightarrow n_{ij}^{\mathrm{ref}} = \frac{\log\left(\mathrm{RSSI}_{ij}^{\mathrm{ref,clean}}\right) - \log\left(\mathrm{RSSI}_{\mathrm{close}}\right)}{\log\left(d_{\mathrm{close}}\right) - \log\left(d_{ij}\right)},
\end{aligned} \tag{26}$$

where $\mathrm{RSSI}_{ij}^{\mathrm{ref,clean}}$ represents the clean signal sent by the j^{th} reference tag and received by the i^{th} reader, d_{ij} indicates the distance between the i^{th} reader and the j^{th} reference tag, and n_{ij}^{ref} is the value of n for the i^{th} reader corresponding to the j^{th} reference tag.

3.1.3. Adaptive-Network-Based Fuzzy Inference System. This study applied the ANFIS to obtain the value of n for the target connected to various readers. The ANFIS model involves three input data, one output data, and five layers. The input data represented as $\mathrm{RSSI}_i^{\mathrm{clean}}$ $(i = 1, 2, 3)$ were clean signals received by the i^{th} reader. The output data were the values of n for readers corresponding to reference tags and the target.

(1) Input Layer. Each input involved three MFs, which can be expressed as follows:

$$O_l^1 = \mu_{\mathrm{RSSI}_{il}^{\mathrm{clean}}}(x), \tag{27}$$

where $\mu_{\mathrm{RSSI}_{il}^{\mathrm{clean}}}(x)$ indicates the first MF of the clean signal received by the i^{th} reader. The MF was a bell-shaped distribution with values ranging from 0 to 1, as shown in (28), where x is the input signal, and a_l, b_l, and c_l are MF parameters.

$$\mu_{\mathrm{RSSI}^{\mathrm{clean}}}(x) = \frac{1}{1 + \left(x - c_l/a_l\right)^{2b_l}}. \tag{28}$$

(2) Rule Layer. The firing strength of the fuzzy rules was calculated as follows:

$$O_m^2 = w_m = \mu_{\mathrm{RSSI}_{1a}^{\mathrm{clean}}}(x) \times \mu_{\mathrm{RSSI}_{2b}^{\mathrm{clean}}}(y) \times \mu_{\mathrm{RSSI}_{2c}^{\mathrm{clean}}}(z), \tag{29}$$

where m is the m^{th} rule; a, b, and c are the semantic tags for the first, second, and third readers, respectively; and $a = b = c = 1, 2, 3$.

(3) Normalization Layer. The firing strength of all rules was normalized using (30).

$$O_m^3 = \overline{w}_m = \frac{w_m}{\sum w_m}. \tag{30}$$

(4) Inference Layer. The output of the normalization layer was multiplied with the fuzzy rules to calculate the result of each rule.

$$O_m^4 = \overline{w}_m f_m = \overline{w}_m\left(p_m x + q_m y + r_m z + s_m\right), \tag{31}$$

where f_m is the m^{th} rule, and p_m, q_m, r_m, and s_m are parameters for the m^{th} rule.

(5) Output Layer. The results yielded in the inference layer were summed to be the output value of the ANFIS.

$$O_1^5 = \sum \overline{w}_m f_m = \frac{\sum w_m f_m}{\sum w_m}. \tag{32}$$

The clean signal of reference tags ($\mathrm{RSSI}_{ij}^{\mathrm{ref,clean}}$) and the n values for reference tags corresponding to various readers (n_{ij}^{ref}) were used as the input and output of training data in the hybrid learning algorithm. Consequently, the optimal ANFIS in the environment was employed to determine the value of n (n_i^{tgt}) for the target corresponding to various readers.

3.1.4. Calculation of the Target Location. The n (n_i^{tgt}) obtained using the ANFIS was incorporated in the modified WCG as follows:

$$\begin{aligned}
x_t &= \frac{\sum x_i/\left(\mathrm{RSSI}_i^{\mathrm{tgt,clean}}\right)^{n_i^{\mathrm{tgt}}}}{\sum 1/\left(\mathrm{RSSI}_i^{\mathrm{tgt,clean}}\right)^{n_i^{\mathrm{tgt}}}},\\
y_t &= \frac{\sum y_i/\left(\mathrm{RSSI}_i^{\mathrm{tgt,clean}}\right)^{n_i^{\mathrm{tgt}}}}{\sum 1/\left(\mathrm{RSSI}_i^{\mathrm{tgt,clean}}\right)^{n_i^{\mathrm{tgt}}}},
\end{aligned} \tag{33}$$

where (x_t, y_t) is the coordinate of the target; (x_i, y_i) is the coordinate of the i^{th} reader; and $\mathrm{RSSI}_i^{\mathrm{tgt,clean}}$ indicates the clean signal sent by the target and received by the i^{th} reader.

4. Experiment Evaluation

This study aims to evaluate whether the proposed algorithm meets the future operational requirements of the smart factory through three practical experimental operations. First, the proposed localization algorithm was verified to be capable of generating a more accurate and stable localization result. Second, the number of reference tags was adjusted to examine whether the localization accuracy was influenced by the number of reference tags used. Finally, the localization environment was interfered with to demonstrate that the proposed localization algorithm can generate the same localization results regardless of the interference.

4.1. Experimental Operation 1. The first experiment was conducted in a 20 m × 10 m smart factory environment, in which three readers, six reference tags, and one target was deployed, as shown in Figure 3. The first experiment comprised two parts. In the first part, the type and number of MFs in the ANFIS in the proposed localization algorithm were altered to determine the parameters that can generate satisfactory localization outcomes. The quality of the localization outcomes depended on the distance difference between the actual location and the estimated location of the

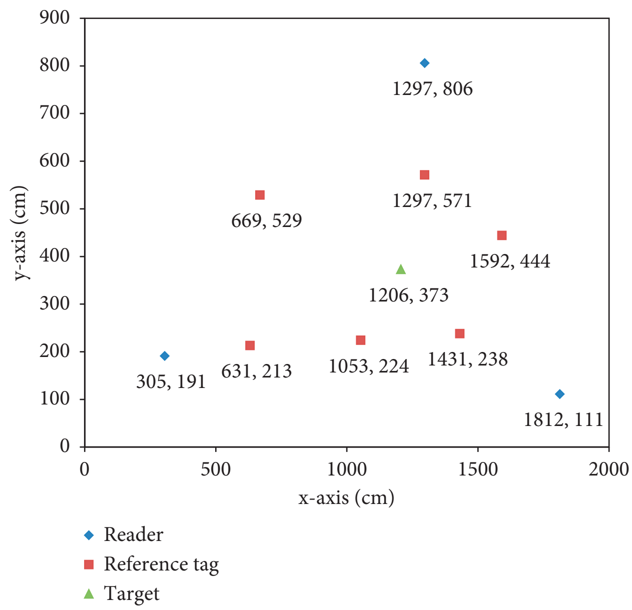


Figure 3: The experiment 1environment.

target given in equation (34) as well as the level of distance difference.

$$E = \sqrt{(x - x_t)^2 + (y - y_t)^2}, \quad (34)$$

where x and y denote the actual x-axis and y-axis coordinate values for the target, and x_t and y_t are the estimated x-axis and y-axis coordinate values for the target, respectively.

The initial state of the system ($\hat{s}_0$) is zero, and the initial covariance (P_0) is 100. By setting the system observation state and initial parameters, the Kalman gain during the calculation process was adjusted and further used to identify the *true* state of the system, enabling covariance convergence.

The localization algorithm proposed in this study categorized the MFs of the ANFIS into three types, namely, triangular-shaped, bell-shaped, and Gauss curves. Two and three MFs were adopted from each type for analysis. Through various combinations of the MFs, the environment parameters that generated superior localization results and were suitable for the target were calculated by employing the MATLAB toolbox for the ANFIS. The experimental results are presented in Table 1.

The standard deviations shown in Table 1 revealed that the results generated using three MFs were more stable compared with those generated using two MFs. Moreover, among the three MF types, the average error produced by the Gauss curve MF was the smallest, and the bell-shaped MF produced optimal stability. Because the Gauss curve and bell-shaped MFs had similar average errors, this study adopted three bell-shaped MFs for the ANFIS parameter setting. The proposed localization algorithm was compared with other frequently used algorithms, such as the LANDMARC [23], WCG [24], ANFIS, and DV-Hop [25] algorithms, and the comparison results are shown in Table 2.

Table 1: The average error in the combination of ANFIS parameters (*cm*).

Membership function type	Number of membership functions			
	2		3	
	Average	Std.	Average	Std.
Triangular-shaped	62.76251	12.74846	67.29013	1.973175
Bell-shaped	77.62174	32.32481	67.02678	1.448937
Gaussian curve	64.05828	24.10496	66.97818	2.119094

Figure 4 shows that the proposed localization algorithm that combined the KF and ANFIS produced minimal localization errors, compared with other algorithms. The comparison presented in Table 2 revealed that the proposed localization algorithm demonstrated optimal localization stability.

The localization results using LANDMARC, WCG, and ANFIS algorithms contained a high number of errors and lacked stability because these algorithms did not consider possible interference in the signal propagation process or the consequent signal distortion. This study applied the concept of reference tag and eliminated noise in the signal transmission process by employing the KF. The propagation path loss model was then used to generate environment parameters, and the environment parameter that was most suitable for the target was obtained using the ANFIS. The weighting method was finally adopted to determine the location of the target. The experimental results indicated that the proposed localization algorithm that combined the KF and ANFIS can be applied to indoor localization.

4.2. Experimental Operation 2. By changing the number of reference tags, the experiment in this experiment aimed to verify whether the number of reference tags influenced the localization results produced by the proposed localization algorithm. Thus, the number of reference tags was set as three and six. The experiment was conducted in a 5 m × 6 m smart factory environment (Figures 5 and 6).

Table 3 indicates that the proposed localization algorithm produced stable localization results regardless of using three or six reference tags; however, the result obtained using six reference tags was superior. This can be explained as follows: The proposed localization algorithm applied the ANFIS to calculate possible environment parameters. In the calculation, the data of the reference tags were used as the training data to identify the inference system suitable for the environment. Therefore, using a high number of reference tags, the possible environment parameters can be identified easily, and accurate localization results can be obtained.

4.3. Experimental Operation 3. The experimental results obtained in the second experiment were used in experiment 3. An interference experiment was conducted in a 9 m × 10 m smart factory environment. Specifically, in a localization environment, the transmission of signals was interfered with by human walking. Subsequently, data were analyzed to verify whether the proposed localization algorithm can generate a localization result at a high level of

TABLE 2: The comparison of localization algorithms in operational experiment 1 (cm).

Localization algorithm	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Ave.	Std.
KF + ANFIS	66.27	67.38	64.41	66.83	68.74	67.08	68.47	67.03	1.45
LANDMARC	183.15	190.98	7.94	156.24	99.36	137.83	210.44	140.85	69.26
WCG	110.03	114.57	111.58	123.78	118.89	107.53	115.65	114.58	5.53
ANFIS	457.39	992.63	944.56	1005.2	451.21	107.75	438.15	628.12	351.78
DV-hop	150.86	145.85	146.85	146.86	152.86	152.86	146.86	149	3.08

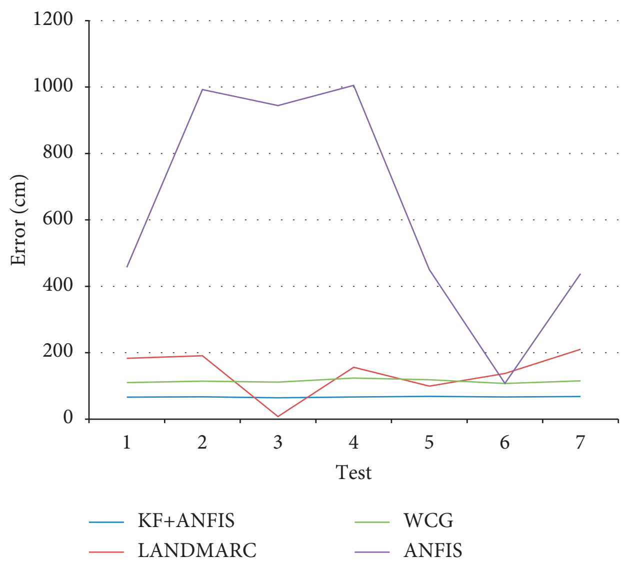


FIGURE 4: The comparison of algorithms in experiment 1.

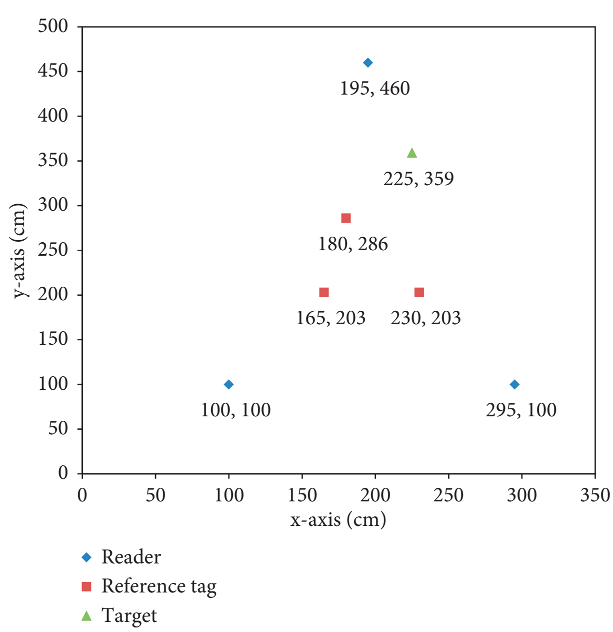


FIGURE 5: The second experimental smart factory environment in which three reference tags were used.

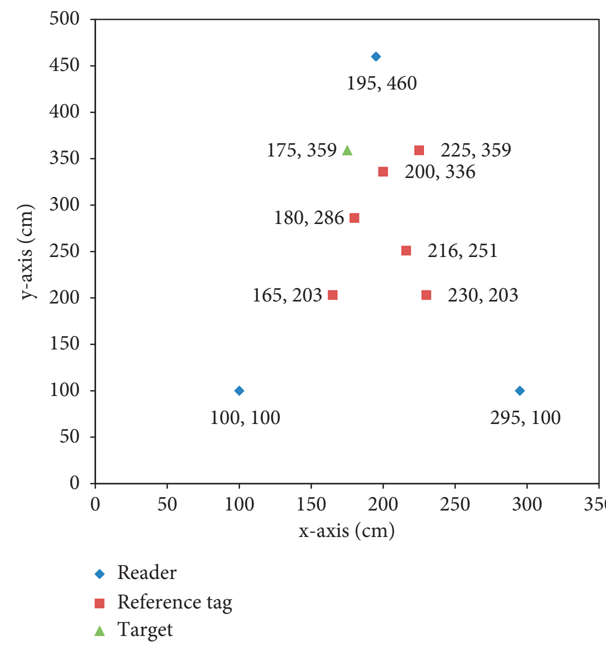


FIGURE 6: The second experimental smart factory environment in which six reference tags were used.

accuracy and stability. The third experimental environment is shown in Figure 7.

Because the proposed localization algorithm applied the KF to eliminate noise during the signal transmission process, the interference of human walking did not cause the localization results to change significantly. Table 4 and Figure 8 show that the tests with and without interference produced similar average errors and stable localization results.

In this study, we compared the proposed method with the current common localization algorithms (LANDMARC, WCG, ANFIS, and DV-Hop) operated in the smart factory environment through experimental operation 1; the results confirm that the proposed algorithm has significantly improved the localization error and is relatively stable (lowest value of standard deviation). Furthermore, experimental operation 2 was used to verify whether the larger the number of reference tags, the more it interferes with the accuracy of localization in the smart factory environment; as a result, in the smart factory environment, the more the number of reference tags is in the proposed algorithm, the more likely it is to find the possible interference parameters and to obtain more accurate localization results. However, in the real-life application, it is not possible to completely exclude the interference of the movement of people on the positioning. Therefore, in experimental operation 3, we verified whether the interference of human movement on the signal transmission affects the accuracy and stability of localization in the smart factory environment. Overall, we conclude that

Table 3: Comparison of results produced by using different numbers of reference tags in the second experiment (cm).

Number of reference tags	Test 1	Test 2	Test 3	Ave.	Std.
3	381.8165	380.849	381.6782	381.4479	0.523236
6	311.3723	311.1209	312.0504	311.5145	0.480825

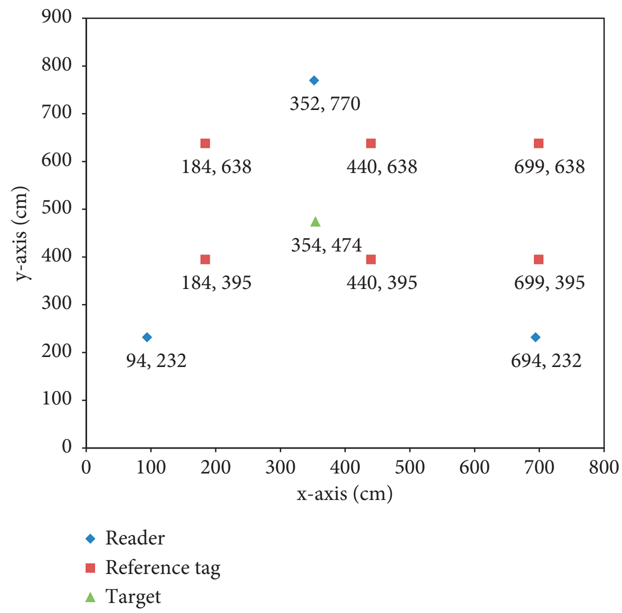


Figure 7: The third experimental smart factory environment.

Table 4: Comparison of results produced in the smart factory environment with and without interference in the third experiment (cm).

Interference	Test 1	Test 2	Test 3	Test 4	Test 5	Ave.	Std.
With interference	69.6928	73.5907	72.4379	72.4057	71.1581	71.8571	1.4846
Without interference	69.046	72.423	68.206	69.9684	69.9193	69.9125	1.5786

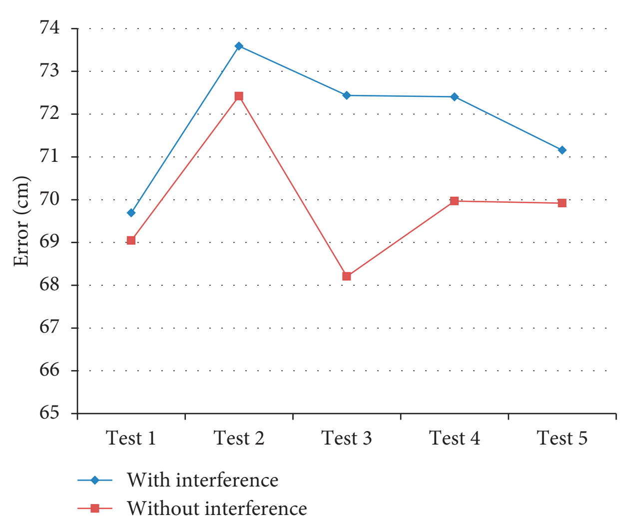


Figure 8: Comparison of errors produced in the smart factory environment with and without interference in the third experiment.

regardless of the interference of signal transmission caused by the movement of people, there is no effect on the positioning results in terms of average positioning error or stability.

5. Conclusion

Traditional localization algorithms based on signal strength cannot produce accurate localization results because of the multipath effect. This study provides a practical contribution by offering an adaptive tracking system with improved tracking algorithms. The system combines KF and ANFIS and applies the concept of reference tags to a smart factory environment. Compared with the positioning error derived from the conventional ANFIS algorithm, the hybrid positioning algorithm (KF + ANFIS) provided in this study reduces the positioning error by up to 89% (=(628.12–67.03)/628.12). Compared with other common localization algorithms, including LANDMARC, WCG, and DV-Hop, the localization error is also reduced by at least 50%. Specifically, the KF was employed to eliminate noise in signal transmission, and a propagation path loss model was adopted to obtain the environment parameters in signal transmission. Through the learning of the ANFIS, the environment parameter most suitable for the target was generated and was subsequently used in the weighting method to determine the location of the target. This technology can be applied not only in smart factories but also in the marketing field. In recent years, it has been proposed to provide local advertising with the user's location information. This helps to market products and services. The contribution of this study can improve the accuracy of indoor positioning and reduce the provision of misinformation.

Moreover, this study involved experimenting in a real environment for parameter setting, and the proposed localization algorithm was compared with other commonly used localization algorithms. The data analysis revealed that the proposed localization algorithm can produce an accurate and stable localization result superior to that produced by others. In addition, experiments regarding the number of reference tags and interference in a localization environment were conducted in this study. The experimental result revealed that an increase in the number of reference tags can cause an increase in localization accuracy. The proposed localization algorithm can produce stable localization results with similar errors regardless of interference in the localization environment.

Although the results produced by the localization algorithm proposed in this study still involved errors, a certain level of stability was achieved. Future studies can identify the stability errors in an environment to obtain an accurate localization result. The combination of various types and numbers of MFs in the ANFIS can be used to improve the accuracy of the localization result for self-propelled inspection robots, thereby effectively reducing the related costs. This location-based service technology can effectively provide accurate equipment information that widely applies in warehouse management, transportation, personnel tracking, and medical care.

Data Availability

"No data were used to support this study".

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was partially supported by the Ministry of Science and Technology of Taiwan under grant no. MOST 110-2221-E-992-086.

References

[1] Y.-C. Chiu, F.-T. Cheng, and H.-C. Huang, "Developing a factory-wide intelligent predictive maintenance system based on Industry 4.0," *Journal of the Chinese Institute of Engineers*, vol. 40, no. 7, pp. 562–571, 2017.

[2] B. Park and J. Jeong, "A CPS-based IIoT architecture using level diagnostics model for smart factory," in *Computational Science and its Applications – ICCSA 2020*, O. Gervasi, Ed., Springer International Publishing, New York, NY, USA, pp. 577–587, 2020.

[3] Z. Huang, J. Zhu, J. Lei, X. Li, and F. Tian, "Tool wear monitoring with vibration signals based on short-time fourier transform and deep convolutional neural network in milling," *Mathematical Problems in Engineering*, vol. 2021, Article ID 9976939, 14 pages, 2021.

[4] H. Yu, K. Wang, R. Zhang et al., "An improved tool wear monitoring method using local image and fractal dimension of workpiece," *Mathematical Problems in Engineering*, vol. 2021, Article ID 9913581, 11 pages, 2021.

[5] J. Zhou and J. Shi, "RFID localization algorithms and applications-a review," *Journal of Intelligent Manufacturing*, vol. 20, no. 6, pp. 695–707, 2009.

[6] A. R. C. Claridades and J. Lee, "Developing a data model of indoor points of interest to support location-based services," *Journal of Sensors*, vol. 2020, Article ID 8885384, 16 pages, 2020.

[7] R. J. Kuo, W. L. Tseng, F. C. Tien, and T. Warren Liao, "Application of an artificial immune system-based fuzzy neural network to a RFID-based positioning system," *Computers & Industrial Engineering*, vol. 63, no. 4, pp. 943–956, 2012.

[8] G. M. Mendoza-Silva, J. Torres-Sospedra, and J. Huerta, "A meta-review of indoor positioning systems," *Sensors*, vol. 19, no. 20, p. 4507, 2019.

[9] J. Shang, X. Hu, F. Gu, D. Wang, and S. Yu, "Improvement schemes for indoor mobile location estimation: a survey," *Mathematical Problems in Engineering*, vol. 2015, Article ID 397298, 32 pages, 2015.

[10] U. Carrasco, P. D. Urbina Coronado, M. Parto, and T. Kurfess, "Indoor location service in support of a smart manufacturing facility," *Computers in Industry*, vol. 103, pp. 132–140, 2018.

[11] J. Cheng, J. Hou, C. Yan, J. Cheng, and Q. Zhang, "Chinese location word recognition using service context information for location-based service," *Mathematical Problems in Engineering*, vol. 2014, Article ID 585634, 6 pages, 2014.

[12] L. Ni, D. Zhang, and M. Souryal, "RFID-based localization and tracking technologies," *IEEE Wireless Communications*, vol. 18, no. 2, pp. 45–51, 2011.

[13] G.-X. Liu, L.-F. Shi, J.-H. Xun, S. Chen, L. Zhao, and Y.-F. Shi, "An orientation estimation algorithm based on multi-source information fusion," *Measurement Science and Technology*, vol. 29, no. 11, Article ID 115101, 2018.

[14] P. J. Bevelacqua, "The Friis equation," http://www.antenna-theory.com/basics/friis.php.

[15] J. Yim, S. Jeong, K. Gwon, and J. Joo, "Improvement of Kalman filters for WLAN based indoor tracking," *Expert Systems with Applications*, vol. 37, no. 1, pp. 426–433, 2010.

[16] J.-L. Rullán-Lara, S. Salazar, and R. Lozano, "Real-time localization of an UAV using kalman filter and a wireless sensor network," *Journal of Intelligent and Robotic Systems*, vol. 65, no. 1–4, pp. 283–293, 2012.

[17] G. Welch and G. Bishop, *An Introduction to the Kalman Filter*, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA, 1995.

[18] J.-S. R. Jang, "ANFIS: adaptive-network-based fuzzy inference system," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 23, no. 3, pp. 665–685, 1993.

[19] T. Oliveira, M. Raju, and D. P. Agrawal, "Accurate distance estimation using fuzzy based combined RSSI/LQI values in an indoor scenario: experimental verification," *Network Protocols and Algorithms*, vol. 4, no. 4, pp. 174–199, 2012.

[20] H. Lee, J. Jung, K. Choi, J. Park, and H. Myung, "Fuzzy-logic-assisted interacting multiple model (FLAIMM) for mobile robot localization," *Robotics and Autonomous Systems*, vol. 60, no. 12, pp. 1592–1606, 2012.

[21] B. K. Patle, D. R. K. Parhi, A. Jagadeesh, and S. K. Kashyap, "Application of probability to enhance the performance of fuzzy based mobile robot navigation," *Applied Soft Computing*, vol. 75, pp. 265–283, 2019.

[22] L. B. Cosme, W. M. Caminhas, M. F. S. V. D'Angelo, and R. M. Palhares, "A novel fault-prognostic approach based on interacting multiple model filters and fuzzy systems," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 1, pp. 519–528, 2019.

[23] L. M. Ni, Y. Liu, Y. C. Lau, and A. P. Patil, "LANDMARC: indoor location sensing using active RFID," *Wireless Networks*, vol. 10, no. 6, pp. 701–710, 2004.

[24] K. K. H. Kan, S. K. C. Chan, and J.-Y. Ng, "A dual-channel location estimation system for providing location services based on the GPS and GSM networks," in *Proceedings of the 17th International Conference on, 2003*, pp. 7–12, IEEE, San Francisco CA USA, June 2003.

[25] K. Jiang, L. Yao, and J. Feng, "Wireless sensor networks target localization based on least square method and DV-hop algorithm," *Journal of Networks*, vol. 9, no. 01, pp. 176–182, 2014.

Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 4416270, 12 pages
https://doi.org/10.1155/2021/4416270

Research Article

Evaluate the Consumer Acceptance of AIoT-Based Unmanned Convenience Stores Based on Perceived Risks and Technological Acceptance Models

I-Chi Wang,[1] Chin-Wen Liao,[1] Kuo-Ping Lin ,[2] Ching-Hsin Wang,[3] and Cheng-Lin Tsai[3]

[1]*Department of Industrial Education and Technology, National Changhua University of Education, Changhua, Taiwan*
[2]*Department of Industrial Engineering and Enterprise, Information, Tunghai University, Taichung, Taiwan*
[3]*Department of Leisure Industry Management, National Chin-Yi University of Technology, Taichung, Taiwan*

Correspondence should be addressed to Kuo-Ping Lin; kplin@thu.edu.tw

Received 8 May 2021; Accepted 21 June 2021; Published 28 July 2021

Academic Editor: Kuei-Hu Chang

As the Artificial Intelligence Internet of Things (AIoT)-based unmanned convenience stores stand out in an increasingly challenging market, the consumer experience is more important than ever (CustomerThink, 2018). By employing new technologies, 7-Eleven, a leading chain convenience store in Taiwan, launched X-Store in 2018. While AIoT-based unmanned technology can help solve the problem of manpower shortages in the future, a question arises: will people accept this new technology for shopping? In view of this and based on the technology acceptance model (TAM), this study adds perceived risk as another variable to explore the impact of perceived usefulness, perceived ease of use, and attitudes toward using unmanned technology etc. factors on the purchase intentions of consumers in unattended convenience stores. The study further employs SPSS software for reliability and validity analyses, descriptive statistics, multivariate analysis of variance (MANOVA), and structural equation modeling (SEM) in order to explore the causal relationship among the variables herein. The main empirical findings show that consumers' perceived ease of use and perceived usefulness positively affect consumers' attitudes toward making purchases in X-Store, and via the moderating effect, perceived usefulness and attitudes toward X-Store consumption impact consumers' behavioral intention of purchasing products in X-Store. In addition, perceived risk has a significant moderating effect on attitudes toward using X-Store and behavioral intentions. The empirical results also reveal that male consumers have significantly greater perceived usefulness, perceived ease of use, attitudes toward using, and behavioral intentions in comparison with female consumers. Finally, this study presents conclusions and recommendations based on the research results as reference for unattended convenience store operators and follow-up researchers.

1. Introduction

With the decline of the fertility rate and human needs for innovative development, smart technology is becoming increasingly advanced. According to the Statistics Department of the Ministry of Economic Affairs in 2019, there were 11,465 convenience stores in Taiwan, ranking second in the world in density, with one convenience store for every 2,058 people on average. In addition, the turnover of convenience stores hits TWD 331.6 billion NTD in 2019. It not only maintains a positive growth for 20 consecutive years but also expects to reach a new high this year [1]. At the end of 2016, Amazon [2], the leading e-commerce company in the United States, predicted a possible new look of retail stores in the future; it launched "Amazon Go," which ushered in a new era for unmanned stores. As the development of unmanned stores gathers momentum throughout the world, unmanned technology has become a new trend in the future [3–6].

The consumption experience that combines smart technology with physical stores has already emerged; traditional cash transaction is transformed into online electronic payment with cash replaced by virtual currency. In this context, the study aims to explore consumer behaviors toward AIoT-based unmanned convenience stores and the factors that influence consumers to use them. Considering unmanned convenience stores as a new technological model, the study uses the technology acceptance model (TAM) as its theoretical basis for it is widely accepted [7–10]. In addition, the promotion of AIoT-based unmanned convenience stores in Taiwan is slow in comparison with some countries. Therefore, the variable perceived risk is added to this study in order to explore whether consumption intentions of consumers in Taiwan are affected by the aforementioned factors when they are in AIoT-based unmanned convenience stores.

A majority of Taiwanese consumers are highly dependent on services of convenience stores. With the help of innovative technology, AIoT-based unmanned convenience stores are introduced by the leading convenience store chain 7-Eleven. Traditional convenience stores are still booming, but the rise of X-Store seems to mark the transition of Taiwan's convenience stores. In this context, whether new technology is accepted by the public when buying at convenience stores remains a question to be explored.

People must have perceived risks when they avail of the convenience and the service provided by the rising X-Store. Under this circumstance, it is unsure whether the existence value of X-Store can be recognized by Taiwan's consumers. Therefore, this study employs TAM and the variable of perceived risk. To be more specific, the objectives of this study are as follows:

(a) To help investors figure out important concerns of Taiwan's customers that influence their behaviors toward X-Store, the TAM is adopted to find out whether customers' feelings of the new technology service provided by X-Store have a positive influence on their attitude towards X-Store. It can be a reference for the future development of other unmanned stores and help reduce potential resistance.

(b) This research aims to find out the extent to which Taiwanese customers recognize AIoT-based unmanned convenience stores after they gained an understanding of the service provided by such stores through watching a video.

(c) Which risks are the biggest concerns of Taiwanese consumers? If these perceived risks exist, will they influence the behaviors of Taiwanese consumers toward unattended convenience stores?

2. Literature Review

2.1. Perceived Risk. According to Chen and Chen [11] and Chen et al. [12], the quality of experience refers to the psychological consequences produced by consumers' participation in purchasing activities. It not only involves the attributes of services provided by suppliers, but also the psychological perception brought by consumers. Bauer [13] first proposed the concept of perceived risk in 1990. He believes that unpredictable results may occur when consumers make purchases, which are often negative. Cox further explained that perceived risk may be derived from customers' failure in meeting their expectations. In addition, risks increase as the Internet is widely used in marketing. Online selling can do better than the traditional way of providing product descriptions to meet customers' visual and auditory satisfaction. It is also a new way of virtual retailing. Information asymmetry, inability to experience the product, and having no direct feeling of a product and its features increase uncertainty and make customers doubtful about shopping websites. Therefore, shopping online generates higher perceived risks compared with traditional shopping at physical stores.

In addition, Akaah and Korgaonkar [14] pointed out that when shopping situation changes, the perceived risks of customers also change. Stone and Grønhaug [15] define perceived risks as "possible losses in pursuit of a desired outcome." Swaminathan et al. [16] proposed that the most important thing in online shopping is transaction security. Higher transaction security produces a lower level of perceived risks and makes consumers more willing to make purchases. Therefore, the perceived risk is defined as "the risks that consumers feel in transactions when they shop online." Forsythe and Shi [17] define the perceived risk of online shopping as the expected loss of an online shopper when he/she making a decision.

Based on the viewpoints of the above scholars, this study defines the perceived risks of online shopping as the risk assessment made by shoppers in order to pursue expected results when they decide to shop online. That is to say, people change their decision based on their subjective cognition of potential loss and risk. Risks mainly consist of six types, namely, financial risk, performance risk, physical risk, psychological risk, social risk, and time risk.

2.2. Unmanned Store. Thanks to the rapid growth of high-end technologies such as the Internet of Things (IoT) and artificial intelligence (AI), unmanned stores that feature "Low-Touch Service" are brought to our daily lives [18]. The technologies applied to the most commonly seen unmanned stores can be classified into two categories: AI and IoT. AI employs technologies such as biopayment, facial or biological recognition, vision sensor, and deep learning to function as machines' eyes and brains. Intelligent consumption is achieved through identity confirmation and automatic checkout, and customers can even directly "take away" products. This model is followed by "Amazon Go" by Amazon, the intelligent convenience store "Take Go" by Hangzhou Wahaha Group Co., Ltd. and DeepBlue Technology (Shanghai) Co., Ltd., and the unmanned store that is being tested and developed by the Industrial Technology Research Institute. The second kind is IoT utilizes Radio Frequency Identification (RFID) readers, barcode scanners, sensors, and other technologies to check out. For example, the Bingo Box, an unmanned convenience store developed by RT-Mart and Auchan uses RFID technology; customers choose products with RFID tags in the Bingo Box, after which they can scan the product identification code, pay for the products that they have chosen, and collect payments automatically [19, 20].

AI and IoT are two core technologies, and the third kind of interactive use that integrates AI with IoT has emerged. Taiwan's X-Store and NEC mainly use the third technology. They combine the third type of technology with the intelligent identification system that can be used to identify humans and items without much-complicated calculation or installing a number of sensors. The combination makes this technology connect humans, items, and consumption easily and manage the whole shopping process.

In addition, vending machines have existed in the market for a long time. Take the F5 Future Store as an example; it is similar to a large vending machine. Robotic arms are used to pick up items, and the biggest selling point is that it sells fresh food products. Located in Wanhua District, Taipei of Taiwan, the "O2O Unmanned Convenience Store" of Green Taste also uses many vending machines to sell beverages and foods and customers are required to use Easy Cards for recognition. In brief, unmanned convenience stores mainly rely on AI and IoT technologies such as vision sensors, facial or biological recognition, deep learning, and RFID. The fundamental task is to integrate and link various intelligent terminals and AI platforms for data analysis and cloud solutions.

2.3. Technology Acceptance Model. The technology acceptance model (TAM), first proposed by Fred Davis [21] on the basis of the theory of reasoned action, discusses the technology acceptance of a single consumer. It hopes to explore the influences of external variables on users' internal beliefs, attitudes, and intentions with TAM and predict whether intentions can change an individual's behavior toward new technology. In other words, the TAM holds that those who insist that certain technology can improve work efficiency and performance believe the technology is easy to operate, and then their attitude toward using the technology will be more favorable and positive. As a result, users' willingness to use the technology will be improved. Therefore, numerous studies have applied the technology acceptance model (TAM) to the fields of information, finance, consumption, research and development, etc. and have received remarkable outcomes [22–26].

3. Research Method

3.1. Research Framework. This research centers on X-Store which embodies a new technology concept of AIoT-based unmanned convenience stores and uses the technology acceptance model (TAM) as the theoretical basis to explore users' acceptance of emerging technology applications. This study means to find out whether there are factors that affect consumers' decision-making. To answer this question, this study collected data about moderating variables which may affect people's final decisions based on the literature; previous studies have revealed that perceived risks exert an impact on users' behavioral intentions and attitudes. Consequently, this study sets perceived risk as the moderating variable that influences consumers' attitudes and behavioral intentions to find out whether the variable would affect people's final decision-making. In addition, this study aims to investigate consumers' attitudes toward using X-Store and their acceptance of it after they understood its overall operation. The research framework is shown in Figure 1.

3.2. Research Hypothesis. Based on the research motivation and objectives, the literature review, and research framework, this study proposes hypotheses shown as follows.

3.2.1. The Effect of Perceived Ease of Use on Perceived Usefulness. Benbasat and Dexter [27] and Davis and Venkatesh [28] pointed out that consumers' perceived ease of use for technology products increases their perceived usefulness. Shih [29] and Van der Heijden [30] also found that when consumers think that a technology product is easy to use, they will increase their recognition for the product. Accordingly, the first hypothesis is proposed as follows:

H1: the higher the perceived ease of use is, the higher the perceived usefulness will be.

3.2.2. The Impact of Perceived Ease of Use on Attitudes toward Using X-Store. Dishaw and Strong [31]; Moon and Kim [32]; and Van der Heijden [30] pointed out that if consumers find it easy to use a technology product, they will maintain a positive attitude toward using it, which leads to the following hypothesis:

H2: the higher the perceived ease of use is, the more positive the attitudes toward using X-Store consumers will have.

3.2.3. The Impact of Perceived Usefulness on Attitudes toward Using X-Store. Perceived usefulness means that if users' actual performance improves after using new technology, they will generate a sense of recognition for it. According to the studies of Hu et al. [33]; Dishaw and Strong [31]; and Bruner II and Kumar [34], if users feel that their work efficiency improves or they achieve better performance after using a technology product, they will recognize its usefulness. This also has a positive impact on their attitudes toward using it. In this respect, a hypothesis is proposed as follows:

H3: the higher the degree of perceived usefulness of X-Store, the more favorable the attitude toward using X-Store consumers will have.

3.2.4. The Effect of Perceived Usefulness on Behavioral Intentions. According to the studies of Hu et al. [33]; Dishaw and Strong [31]; and Bruner II and Kumar [34], if users feel that what they expected to do improves after using a technology product, their intentions to use this product will also be improved. In this aspect, the following hypothesis is proposed:

H4: the higher the perceived usefulness users have for X-Store, the higher their behavioral intentions to visit it again.

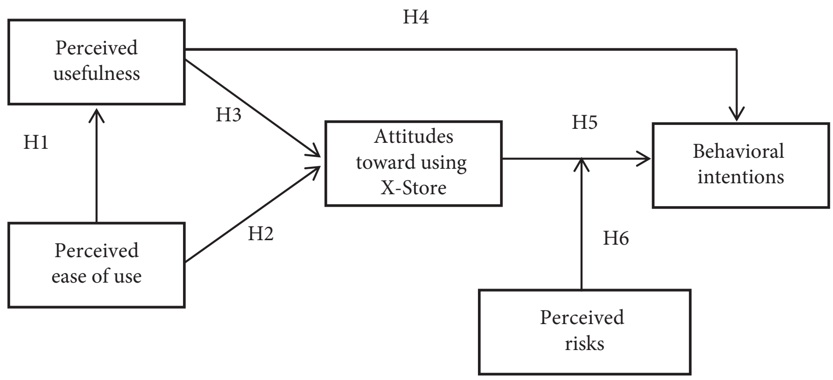


Figure 1: Research framework.

3.2.5. The Impact of Attitudes toward Using X-Store on Behavioral Intentions. According to the studies of Hu et al. [33]; Moon and Kim [32]; Van der Heijden [30]; and Bruner II and Kumar [34], if users have a positive feeling toward what they expect to do after using a technology product, they will use the product more in the future, which leads to the following hypothesis:

H5: the more positive the attitudes toward using X-Store users take, the higher their behavioral intention will be.

3.2.6. Moderating Effects of Perceived Risks, Attitude toward Using X-Store, and Behavioral Intentions. Featherman and Pavlou [35] pointed out in their e-commerce research that perceived risk has a negative effect on perceived usefulness. In addition, Sönmez and Graefe [36] found that perceived security and risk (perceived risks) push people to avoid traveling rather than planning another tour. The following hypothesis is proposed accordingly:

H6: the perceived risk has a moderating effect on users' attitudes toward and behavioral intentions of using X-Store.

4. Data Analysis

According to the research framework and research hypotheses proposed in previous sections, this study adopted a questionnaire survey to collect data and used SPSS, descriptive statistical analysis, and the MANOVA for reliability and validity analysis. Moreover, the SEM was used to analyze the causal relationship between variables in the research framework.

4.1. Questionnaire Collection. This study used the convenience sampling method to collect important data from online questionnaires. The research participants were consumers who had gone to convenience stores in Taiwan. The questionnaires were measured by a five-point Likert scale. The higher score respondents provide also means a higher degree to which they agree with the items. In order to ensure that the respondents were all Taiwanese consumers and the items were definite, this research used the Google online questionnaires that were distributed in private groups of the application Line. The data were collected from February 1, 2019, to March 28, 2019. During this period, a total of 249 copies were issued with 249 valid questionnaires returned. The effective questionnaire recovery rate was 100%. The collected data are sufficient for the required samples to be tested in this study.

4.2. Reliability and Validity Analysis of Formal Survey. In order to guarantee the questionnaire reliability and validity, this study conducted the reliability and validity analysis on 249 valid questionnaires. In this study, the questionnaire reliability and validity are evaluated with Cronbach's α value and exploratory factor analysis. According to Hair et al. [37], if Cronbach's α value is greater than 0.7, it indicates the high internal consistency which can be called as high reliability. Kerlinger [38] proposed that the correlation coefficient of item to total is required to meet the decision criteria of being greater than 0.5. This study results show that Cronbach's α value and correlation coefficients of all dimensions meet the criteria; as a result, the overall questionnaire reliability of this study is good (see Table 1).

As for validity analysis, the exploratory factor analysis (EFA) was used to verify the questionnaire convergent validity. The factors with the characteristic values greater than 1 are extracted by the principal component analysis. By the varimax rotation analysis, it is learnt that the variables under the 5 dimensions, such as perceived ease of use, perceived usefulness, perceived risks, attitudes toward using X-Store, and behavioral intentions, can be classified into the same factors. The factor loadings of all variables in all the factors are larger than 0.5, and the cumulative explained variances of all the factors are larger than 50%, which indicates that all the questionnaire dimensions have the convergent validity (see Table 1).

This study evaluated the reliability and the validity based on the two indexes which are the composite reliability (CR) of latent variables and the average variance extracted (AVE) of latent variables. The decisions are made on the principle that the CR value is greater than 0.6 and the AVE value is greater than 0.5 [39]. The values of composite reliability (CR) of latent variables in all factors are between 0.911 and 0.944 and larger than 0.6, indicating that all the dimensions of this study have good internal consistency. The average variance extracted (AVE) of latent variables is ranged from 0.598 to 0.848, which is larger than 0.5 and meets the ideal value,

Table 1: Reliability and validity analysis of formal survey ($n = 249$).

Construct	Measurement items	Item-to-total correlation coefficient	Factor loading	Eigenvalue	Cumulative explained variation %	Cronbach α value	Component reliability (CR)	Average variance extracted (AVE)
Perceived ease of use	I think shopping at the X-Store would not expend much of my energy	0.880	0.947	2.676	89.210	0.940	0.940	0.838
	I think shopping at the X-Store can be easy	0.878	0.946					
	I think the facilities and services at the X-Store are easy to use	0.865	0.940					
Perceived usefulness	Using X-Store can improve my shopping convenience	0.898	0.955	2.693	89.767	0.943	0.944	0.848
	Using X-Store can improve my shopping efficiency	0.877	0.946					
	Shopping in the X-Store is good for me	0.868	0.941					
Perceived risks	I have no confidence in the operation of the facilities or services provided by the X-Store	0.833	0.889	4.672	68.023	0.921	0.911	0.598
	I am concerned that the products or services provided by the X-Store are not meeting my expectations	0.786	0.855					
	I may feel uneasy about making purchases in an X-Store without clerks	0.787	0.854					
	I would worry that the value of the product or service provided by the X-Store is not in line with my expectations	0.775	0.842					
	I would worry that the services provided by the X-Store would not work properly and cause financial losses	0.719	0.790					
	I would worry that the facial recognition system of X-Store would not work properly and make me not be able to enter and exit the store smoothly	0.697	0.775					
	I would worry about the property loss caused by theft of data or passwords when using the X-Store's automatic checkout system	0.683	0.760					
Attitudes toward using X-Store	I like the concept of X-Store	0.870	0.944	2.602	86.734	0.923	0.925	0.803
	I think using X-Store is a good idea	0.836	0.927					
	I think making purchases at X-Store is a wise decision	0.828	0.923					
Behavioral intentions	The shopping experience provided by X-Store will increase my willingness to make purchases in it	0.883	0.951	2.591	86.369	0.921	0.939	0.838
	I may use X-Store frequently in the future	0.823	0.921					
	If I have the opportunity, I will use X-Store	0.814	0.916					

indicating that all the dimensions have the convergent validity (see Table 1).

4.3. Narrative Statistics of Taiwanese Consumers' Perceived Ease of Use, Perceived Usefulness, Perceived Risks, Attitudes toward Using X-Store, and Behavioral Intentions. The first question that this study aims to explore is the important factors affecting Taiwanese consumers' behaviors in the X-Store. In Table 2, to collect data about the Taiwanese consumers' perceived ease of use, perceived usefulness, perceived risks, attitudes toward using the store, and behavioral intentions of consumer behaviors in the X-Store, SPSS was used to perform descriptive statistical analysis. According to the averages of the intention, a higher score represents more attention.

(1) How Taiwanese consumers feel whether the facilities in X-Store are easy to operate is shown in Table 2, the mean for the item "I think shopping at the X-Store can be easy" is the highest 3.8313 (SD = 1.1197) while the item "I think the facilities and services at the X-Store are easy to use" had the lowest mean 3.6426 (SD = 1.1309). It can be seen that most Taiwanese consumers had not found it relaxing and easy to use the facilities at the X-Store and their attitudes toward using its services remained relatively neutral.

(2) Taiwanese consumers' views on whether the facilities at the X-Store are useful are shown in Table 2. The mean of the item "using X-Store can improve my shopping convenience" is the highest 3.6225 (SD = 1.1154) while the item "shopping in the X-Store is good for me" had the lowest mean 3.5422 (SD = 1.1213). It can be seen that most Taiwanese consumers do not particularly enjoy the convenience of shopping at the X-Store nor do they have a strong feeling of assistance given by the devices at the store.

(3) How Taiwanese consumers feel about the potential risks when they make purchases at the X-Store is shown in Table 2. The mean of the item "I would worry about the loss of property caused by theft of data or passwords when using the X-Store's automatic checkout system" is the highest 3.7791 (SD = 1.1826), and the mean of the item "I have no confidence in the operation of the facilities or services provided by the X-Store" is the lowest 3.0522 (SD = 1.1576) It can be seen that most Taiwanese consumers pay much attention to financial security and maintain a relatively neutral attitude toward the services provided by X-Store.

(4) Whether the facilities and services provided by the X-Store have a positive impact on Taiwan consumers' attitudes toward using X-Store is shown in Table 2. The item "I think using X-Store is a good idea" has the highest mean 3.8353 (SD = 1.0930) while the item "I think spending at X-Store is a wise decision" 3.5542 (SD = 1.0463) has the lowest mean. It can be seen that although most Taiwanese consumers thought that the X-Store idea is good, most consumers did not significantly feel that X-Store makes their life more convenient.

(5) In terms of whether the facilities and services provided by the X-Store have a positive impact on the behavioral intentions of Taiwanese consumers, as shown in Table 2, the item "if I have the opportunity, I will use X-Store" has the highest mean 3.9398 (SD = 1.1361) while the item "I may use X-Store frequently in the future" has the lowest mean 3.5181 (SD = 1.1573). It can be seen that most consumers are less willing to use the services provided by the X-Store or do not intend to use X-Store frequently in the future. The mean of the item "if I have the opportunity, I will use X-Store" has the highest mean. This may happen because most consumers are willing to have a try before actually experiencing shopping in the X-Store.

4.4. Multivariate Analysis of Variance. The second question that this study aims to explore is how many Taiwanese consumers recognize AIoT-based unmanned convenience stores after learning about the latest technological services provided by such stores. As shown in Table 3, to figure out the differences from the perspective of gender, this study uses multivariate analysis of variance (MANOVA) to know the means and significance between different factors to analyze the degree to which consumers recognize perceived ease of use, perceived usefulness, perceived risk, attitude toward using, and behavioral intention between male and female research participants.

4.4.1. Perceived Usefulness. As shown in Table 3, the P values of the following factors are all less than 0.05, which suggests a level of significance. According to the means for gender, male participants' means of perceived usefulness are all greater than those of female respondents. The research result shows that male respondents have a higher level of recognition for the services provided by X-Store than female participants.

4.4.2. Perceived Ease of Use. As shown in Table 3, the P values of the following factors are all less than 0.05, which indicates a level of significance. According to the means of male and female participants, the averages of male perceived ease of use are all greater than those of female respondents. The study result shows that male respondents tend to find X-Store devices relatively easier to use than female participants.

4.4.3. Perceived Risk. As shown in Table 3, most of the means of male perceived risk are less than those of female participants. The study result suggests that men relatively care less about the potential risks of shopping at the X-Store than women. The P value of male perceived risks is less than 0.05, which indicates a level of significance.

Table 2: The mean value and standard deviation of measurement items.

Construct	Measurement items	Mean value	Standard deviation
Perceived ease of use	I think shopping at the X-Store would not expend much of my energy	3.7912	1.1019
	I think shopping at the X-Store can be easy	3.8313	1.1197
	I think the facilities and services at the X-Store are easy to use	3.6426	1.1309
Perceived usefulness	Using X-Store can improve my shopping convenience	3.6225	1.1154
	Using X-Store can improve my shopping efficiency	3.5462	1.1738
	Shopping in the X-Store is good for me	3.5422	1.1213
Perceived risks	I have no confidence in the operation of the facilities or services provided by the X-Store	3.0522	1.1576
	I am concerned that the products or services provided by the X-Store are not meeting my expectations	3.1847	1.1350
	I may feel uneasy about making purchases in an X-Store without clerks	3.2530	1.2461
	I would worry that the value of the product or service provided by the X-Store is not in line with my expectations	3.2932	1.2042
	I would worry that the services provided by the X-Store would not work properly and cause financial losses	3.5020	1.2152
	I would worry that the facial recognition system of X-Store would not work properly and make me not be able to enter and exit the store smoothly	3.5783	1.1618
	I would worry about the property loss caused by theft of data or passwords when using the X-Store's automatic checkout system	3.7791	1.1826
Attitudes toward using X-Store	I like the concept of X-Store	3.8273	1.0991
	I think using X-Store is a good idea	3.8353	1.0930
	I think making purchases at X-Store is a wise decision	3.5542	1.0463
Behavioral intentions	The shopping experience provided by X-Store will increase my willingness to make purchases in it	3.6546	1.1748
	I may use X-Store frequently in the future	3.5181	1.1573
	If I have the opportunity, I will use X-Store	3.9398	1.1361

4.4.4. Attitude toward Using. As shown in Table 3, the P values of the following factors are all less than 0.05, indicating a level of significance. The means of male respondents' attitudes toward using X-Store are all greater than those of female respondents. The study result suggests that the degree to which men recognize X-Store is relatively higher than that of women.

4.4.5. Behavioral Intention. As shown in Table 3, the P values of the following factors are all less than 0.05, which indicates a level of significance. The means of male respondents' behavioral intentions are all greater than those of female respondents. The study result suggests that men are relatively more willing to revisit X-Store in the future than women.

4.5. Structural Equation Modeling. The third aim of this study is to find out what kinds of potential risks Taiwanese consumers regard the most important. If these perceived risks exist, it is worth to explore whether they will have an effect on the consumption behaviors of Taiwan consumers towards unattended convenience stores. In this section, the structural equation modeling (SEM) is used to test hypothesis 1 to 6.

4.5.1. Offending Estimates Verification. The measured values of the structure model of this study are shown in Table 4. The standard error is between 0.065 and 0.316, and there is not much standard error; the error variance of measurement is between 0.133 and 0.895, and there is no negative error variance. In addition, the standardized regression coefficient value in the model is between 0.059 and 0.943, and none exceeds 0.95, indicating that the structural model of this study does not violate the estimation.

4.5.2. Confirmatory Factor Analysis. In order to confirm the efficiency of measuring dimensions, this study carried out the confirmatory factor analysis (CFA) with AMOS software on the measurement models of 5 dimensions such as perceived ease of use to AIoT-based unmanned convenience stores, perceived usefulness, perceived risk, attitude to use, and behavioral intentions. According to the model proposed by Carmines and MacIver [40], the fit indicators shall meet the ideal standard; thereinto, the ratio between chi-square value and degree of freedom is no more than 3, RMSEA is less than 0.05, and the values of GFI, AGFI, NFI, RFI, and CFI are greater than 0.9 [41, 42]. The results show that, among the fit indicators of the measurement model, the value of $\chi 2/df$ is 1.960, the value of GFI is 0.902, the value of AGFI is 0.983, the value of NFI is 0.949, the value of RFI is 0.937, the value of CFI is 0.974, and the value of RMSEA is 0.059, except for the chi-square value affected by the sample size, indicating that the fitness of all the measurement models reaches the acceptable range. Therefore, in this study, the fitness of the measurement model is good, representing

Table 3: MANOVA for perceived ease of use, perceived usefulness, perceived risks, attitudes toward using, and behavioral intentions.

Item	Factor	Gender		F value	P value
		Male $N = 88$	Female $N = 161$		
Perceived ease of use	Pillai's trace = 0.046 Wikls' lambda = 0.954	4.0568	3.6000	3.959	0.009
	It will not take me much time to shop at the X-Store	4.1250	3.6708	9.691	0.002
	It is easy for me to shop at the X-Store	4.0795	3.6635	9.646	0.002
	Overall, the devices and services at the X-Store are easy to use for me	3.9659	3.4658	11.601	0.001
Perceived usefulness	Pillai's Trace = 0.036 Wikls' lambda = 0.964	3.8296	3.4286	3.012	0.031
	X-Store can improve my shopping convenience	3.8523	3.4969	5.890	0.016
	X-Store can improve my shopping efficiency	3.8182	3.3975	7.499	0.007
	Overall, shopping at the X-Store is good for me	3.8182	3.3913	8.496	0.004
Perceived risk	Pillai's trace = 0.071 Wikls' lambda = 0.929	3.2490	3.3931	2.624	0.013
	I do not have much confidence in the normal operation of X-Store's facilities and services	3.4091	3.5528	0.795	0.373
	I worry that the products and services at the X-Store do not meet my expectation	3.4545	3.2050	2.459	0.118
	I may feel nervous when shopping at self-service X-Store that has no clerk	3.6477	3.8509	1.685	0.196
	I worry that the value of the products and services in the X-Store do not meet my expectation	3.2386	3.2609	0.018	0.893
	I worry about financial losses because the services at the X-Store may not work well	3.1364	3.2112	0.246	0.620
	I worry that I cannot enter and exit the store freely due to the potential failure of the store's facial recognition system	3.0114	3.0745	0.169	0.681
	I worry about financial losses because my data and password may be stolen when I am using the automatic checkout system at the X-Store	3.5455	3.5963	0.108	0.742
Attitude toward using X-Store	Pillai's trace = 0.045 Wikls' lambda = 0.955	3.9583	3.5652	3.853	0.010
	Overall, I like the idea of X-Store	4.2386	3.7764	9.752	0.002
	I think it is a good idea to shop at the X-Store	3.8636	3.5404	4.366	0.038
	I think it is a wise decision to shop at the X-Store	3.7727	3.3789	6.742	0.010
Behavior intention	Pillai's trace = 0.038 Wikls' lambda = 0.962	3.9773	3.6087	3.196	0.024
	The consumption experience provided by X-Store will increase my willingness to make purchases from the store	4.0568	3.7143	5.694	0.018
	I will probably visit X-Store frequently in the future	3.7614	3.4410	5.429	0.021
	I would like to shop at X-Store if I get a chance	4.1136	3.6708	9.556	0.002

that this measurement index has the construct validity and the measurement efficiency (as shown in Table 5).

4.5.3. Linear Structure Model Analysis. In this study, AMOS software was used to analyze the linear structural relationship model, in order to understand the causality and correlation between variables. According to Forza and Filippini [43], the good model should meet the following: GFI, RFI, AGFI, NFI, and other indicators should be greater than 0.8, CFI value should be greater than 0.9 [44], RMSEA value should be less than 0.05 [45], the measurement standard of $\chi 2/df \leqq 3$ [46] is used as the criterion for checking the suitability of the model.

The analysis results show that this study $\chi 2$ is 255.277, the degree of freedom is 138, P value is 0.00, $\chi 2/df$ is 1.850, GFI is 0.903, AGFI is 0.986, NFI is 0.950, RFI is 0.938, CFI is 0.976, and RMSEA is 0.059. Except that the chi-square value affected by the sample size does not meet the adaptation standard, this result meets the good model standard proposed by scholars, so the structural model suitability is better (as shown in Table 5).

4.5.4. Hypothesis Testing. Through the overall model parameter estimation analysis, as shown in Table 4, the verification results of each hypothesis are as follows:

(1) H1: perceived ease of use has a positive impact on perceived usefulness with a standardized coefficient of 0.928 and T value greater than 1.96 (T value = 9.588), which supports H1. Therefore, if consumers feel that new technology products are easy to use, they will recognize their usefulness.

(2) H2: perceived ease of use has a positive impact on the attitude of X-Store users with a standardized coefficient of 0.535 and T value greater than 1.96 (T value = 3.654), which supports H2. Therefore, if

Table 4: Overall model parameter estimation table.

Path			Standardized regression coefficient	Standard error	T value	P value	Error variance	Squared multiple correlation
H1: perceived usefulness	<---	Perceived ease of use	0.928	0.260	9.588	***	0.153	0.861
H2: attitudes toward using X-Store	<---	Perceived ease of use	0.535	0.272	3.654	***	0.256	0.711
H3: attitudes toward using X-Store	<---	Perceived usefulness	0.323	0.101	2.222	*		
H4: behavior intention	<---	Perceived usefulness	0.175	0.065	2.930	**	0.133	0.881
H4: behavior intention	<---	Attitudes toward using X-Store	0.788	0.171	7.170	***		
H4: behavior intention	<---	Perceived risks	-0.059	0.082	-2.078	*	0.548	0.000
I think shopping at the X-Store would not expend much of my energy	<---	Perceived ease of use	0.912	0.245	18.572	***	0.211	0.831
I think shopping at the X-Store can be easy	<---	Perceived ease of use	0.921	0.240	18.893	***	0.184	0.848
I think the facilities and services at the X-Store are easy to use	<---	Perceived ease of use	0.914	0.247	18.660	***	0.209	0.836
Using X-Store can improve my shopping convenience	<---	Perceived usefulness	0.938	0.150	11.675	***	0.150	0.880
Using X-Store can improve my shopping efficiency	<---	Perceived usefulness	0.909	0.156	11.380	***	0.239	0.826
Shopping in the X-Store is good for me	<---	Perceived usefulness	0.915	0.146	11.596	***	0.201	0.838
I have no confidence in the operation of the facilities or services provided by the X-Store	<---	Perceived risks	0.616	0.316	10.457	***	0.895	0.380
I am concerned that the products or services provided by the X-Store are not meeting my expectations	<---	Perceived risks	0.778	0.291	14.517	***	0.582	0.606
I may feel uneasy about making purchases in an X-Store without clerks	<---	Perceived risks	0.618	0.310	10.517	***	0.860	0.382
I would worry that the value of the product or service provided by the X-Store is not in line with my expectations	<---	Perceived risks	0.838	0.290	16.065	***	0.459	0.703
I would worry that the services provided by the X-Store would not work properly and cause financial losses	<---	Perceived risks	0.900	0.253	18.020	***	0.245	0.809
I would worry that the facial recognition system of X-Store would not work properly and make me not be able to enter and exit the store smoothly	<---	Perceived risks	0.924	0.253	18.686	***	0.194	0.855
I would worry about the property loss caused by theft of data or passwords when using the X-Store's automatic checkout system	<---	Perceived risks	0.675	0.297	11.773	***	0.732	0.455
I like the concept of X-Store	<---	Attitudes toward using X-Store	0.864	0.158	14.343	***	0.302	0.746
I think using X-Store is a good idea	<---	Attitudes toward using X-Store	0.901	0.149	15.255	***	0.207	0.811
I think making purchases at X-Store is a wise decision	<---	Attitudes toward using X-Store	0.923	0.157	15.523	***	0.178	0.852
The shopping experience provided by X-Store will increase my willingness to make purchases in it	<---	Behavioral intentions	0.943	0.162	10.088	***	0.140	0.889

Table 4: Continued.

Path			Standardized regression coefficient	Standard error	T value	P value	Error variance	Squared multiple correlation
I may use X-Store frequently in the future	<---	Behavioral intentions	0.878	0.148	10.623	***	0.310	0.772
If I have the opportunity, I will use X-Store	<---	Behavioral intentions	0.924	0.164	9.901	***	0.190	0.853

Table 5: The goodness-of-fit of the measurement and structural model.

Fit indices		Criteria	Measurement model	Structural model
Absolute fit index	x^2	The smaller the better ($P \geq \alpha$值)	278.104 ($P = 0.004$)	255.277 ($P = 0.000$)
	x^2/df	<3, 1~5	1.960	1.850
	CFI	>0.9	0.902	0.903
	AGFI	>0.9	0.983	0.986
	RMR	<0.08	0.037	0.010
	SRMR	<0.08	0.074	0.074
	RMSEA	<0.08	0.067	0.059
Incremental fit index	NFI	>0.9	0.925	0.950
	NNFI	>0.9	0.958	0.971
	CFI	>0.9	0.962	0.976
	RFI	>0.9	0.937	0.938
	IFI	>0.9	0.970	0.976
Streamline and adapt indicators	PNFI	>0.5	0.765	0.767
	PGFI	>0.5	0.674	0.656

consumers feel that new technology products are easy to use, they will hold a positive attitude toward using them.

(3) H3: perceived usefulness has a positive impact on the attitude of X-Store users toward using it with a standardized coefficient of 0.323 and T value greater than 1.96 (T value = 2.222), which supports H3. Therefore, if consumers feel that new technology products have a positive impact on the way they finish a task, they will take a positive attitude towards using them.

(4) H4: perceived usefulness has a positive impact on the behavioral intention of X-Store users with a standardized coefficient of 0.175 and T value greater than 1.96 (T value = 2.930), which supports H4. Therefore, if consumers feel that new technology products exert a positive impact on the way they finish a task, they are more likely to use them again.

(5) H5: the attitude of X-Store users has a positive effect on their behavioral intention with a standardized coefficient of 0.788 and T value greater than 1.96 (T value = 7.170), which supports H5. Therefore, if consumers take a positive attitude towards new technology products, their behavioral intention will also be positive.

(6) H6: perceived risk has a disturbing effect on X-Store users' attitudes and behavioral intentions. The path coefficient of perceptual risk on usage attitude and behavioral intention is −0.059, and the t value is −2.078 reaching a significant level. This result supports H6, showing that perceptual risk has a negative impact on behavioral intention. In other words, the higher the perceived risk, the lower the consumer's intention to act on this new technology product.

5. Conclusions and Suggestions

5.1. Research Found. This study aims to explore the relationship between Taiwan consumers' perceived usefulness, perceived ease of use, perceived attitude, behavioral intention, and perceived risk for using X-Store. The study finds that the means for most of the factors and items are less than 4.0 while the means of the factors and items for female respondents are all less than 4.0. Regarding the payment, the most common payment method is cash payments for 178 respondents (71.5%), followed by i-cash cards for 27 respondents (10.8%), credit cards for 16 participants (6.4%), mobile payments for 24 participants (9.6%), and other methods of payment for 4 participants (1.6%).

Moreover, research results show that consumers' cognitive process towards X-Store conforms to the technology acceptance model. The perceived ease of use and perceived usefulness of consumers do have a positive effect on their attitude toward using the X-Store; the perceived usefulness and attitude toward using the X-Store of consumers have a positive impact on their behavioral intention of shopping at X-Store. Also, the perceived usefulness and perceived ease of use of consumers can also positively influence the behavioral intention of consumers visiting X-Store through their attitude toward using X-Store.

Furthermore, the study finds that the perceived risk has a significant moderating effect on consumers' behavioral intention of visiting X-Store. Male consumers have a lower extent to which they recognize perceived risks in comparison with female consumers, but they have significantly greater perceived usefulness, perceived ease of use, attitude toward using, and behavioral intentions than female consumers.

5.2. Research Limitations. There are only two X-Stores in Taiwan, and they are both located in Northern Taiwan. Under this circumstance, it is difficult to interview those who have visited X-Store. That is why research participants were required to watch a video before answering the questionnaires to know more about the services provided by X-Store. This is a limitation of this research.

5.3. Suggestions for Future Management. Based on the conclusions of this empirical study, the following suggestions are proposed for reference of unattended convenience store operators and future research.

5.3.1. Promote the i-cash 2.0 Card or Develop Other Electronic Payment Methods. Most of the study participants are female consumers. Research results show that most consumers are accustomed to paying in cash (70%) while those who use i-cash 2.0 cards only account for around 10%. Therefore, if X-Store is promoted in the future, i-cash 2.0 cards should be popularized or other electronic payment methods should be developed. In addition, in order to popularize the electronic payment and make consumers accept it, the diversity and security of i-cash 2.0 cards or the development of other electronic payment methods should be considered, so that it can attract more consumers.

5.3.2. Diversifying Payment Methods. Taiwan's citizens have been used to various services provided by convenience stores and cash payments. If only i-cash cards are accepted, consumers without i-cash cards will not be able to make purchases. This problem can be solved by diversifying payment methods such as mobile payment and cash payment.

5.3.3. Rolling Out New Services. If we want to promote AIoT-based unmanned convenience stores, we cannot simply offer a few basic services. At present, the services provided by X-Store are far fewer than those provided by current convenience stores. Without improving its services, consumers' willingness to shop at X-Store will definitely decline.

Data Availability

The questionnaire survey data used to support the findings of this study are available from the authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] Statistics Department and Ministry of Economic Affairs, Taiwan, "Convenience store exhibits fast stores, and its turnover has repeatedly hit new highs," 2020, https://www.moea.gov.tw/Mns/dos/bulletin/Bulletin.aspx?kind=9&html=1&menu_id=18808&bull_id=7217.

[2] Amazon, *Amazon Go: Frequently Asked Questions*, Amazon, Seattle, WA, USA, 2016, https://www.amazon.com/b?node=16008589011.

[3] M. Hauser, C. M. Flath, and F. Thiesse, "Catch me if you scan: data-driven prescriptive modeling for smart store environments," *European Journal of Operational Research*, vol. 294, no. 3, pp. 860–873, 2021.

[4] Y. S. Hu, L. H. Zeng, Z. L. Huang, and Q. Cheng, "Optimal channel decision of retailers in the dual-channel supply chain considering consumer preference for delivery lead time," *Advances in Production Engineering & Management*, vol. 15, no. 4, pp. 453–466, 2020.

[5] S. Kim and J.-G. Lee, "A systematic framework of predicting customer revisit with in-store sensors," *Knowledge and Information Systems*, vol. 62, no. 3, pp. 1005–1035, 2020.

[6] N. Shekokar, A. Kasat, S. Jain, P. Naringrekar, and M. Shah, "Shop and go: an innovative approach towards shopping using deep learning and computer vision," in *Proceedings of the 3rd International Conference on Smart Systems and Inventive Technology, ICSSIT 2020*, pp. 1201–1206, Tirunelveli, India, August 2020.

[7] A. Bagheri, A. Bondori, M. S. Allahyari, and J. Surujlal, "Use of biologic inputs among cereal farmers: application of technology acceptance model," *Environment, Development and Sustainability*, vol. 23, no. 4, pp. 5165–5181, 2021.

[8] A. Mavroudi, S. Papadakis, and I. Ioannou, "Teachers' views regarding learning analytics usage based on the technology acceptance model," *TechTrends*, vol. 65, no. 3, pp. 278–287, 2021.

[9] A. M. Momani, "A modified technology acceptance theory to assess social commerce technology adoption," *Information Resources Management Journal*, vol. 34, no. 2, pp. 43–62, 2021.

[10] T. K. M. Wong, S. S. Man, and A. H. S. Chan, "Exploring the acceptance of PPE by construction workers: an extension of the technology acceptance model with safety management practices and safety consciousness," *Safety Science*, vol. 139, 2021.

[11] C.-F. Chen and F.-S. Chen, "Experience quality, perceived value, satisfaction and behavioral intentions for heritage tourists," *Tourism Management*, vol. 31, no. 1, pp. 29–35, 2010.

[12] K.-S. Chen, C.-H. Wang, and K.-H. Tan, "Developing a fuzzy green supplier selection model using six sigma quality indices," *International Journal of Production Economics*, vol. 212, pp. 1–7, 2019.

[13] R. A. Bauer, "Consumer behavior as risk taking," in *Dynamic Marketing for a Changing World*, R. S. Hancock, Ed., pp. 389–393, American Marketing Association, Chicago, IL, USA, 1960.

[14] I. P. Akaah and P. K. Korgaonkar, "A conjoint investigation of the relative importance of risk relievers in direct marketing," *Journal of Advertising Research*, vol. 28, no. 4, pp. 38–44, 1998.

[15] R. N. Stone and K. Grønhaug, "Perceived risk: further considerations for the marketing discipline," *European Journal of Marketing*, vol. 27, no. 3, pp. 39–50, 1993.

[16] V. Swaminathan, E. Lepkowska-White, and B. P. Rao, "Browsers or buyers in cyberspace? An investigation of factors

influencing electronic exchange," *Journal of Computer-Mediated Communication*, vol. 5, no. 2, p. JCMC523, 1999.
[17] S. M. Forsythe and B. Shi, "Consumer patronage and risk perceptions in Internet shopping," *Journal of Business Research*, vol. 56, no. 11, pp. 867–875, 2003.
[18] P. V. Esch, Y. Cui, and S. P. Jain, "Stimulating or intimidating: the effect of AI-enabled in-store communication on consumer patronage likelihood," *Journal of Advertising*, vol. 50, no. 1, pp. 63–80, 2021.
[19] B. B. Gupta and S. Narayan, "A survey on contactless smart cards and payment system," *Journal of Global Information Management*, vol. 28, no. 4, pp. 135–159, 2020.
[20] K. K. W. Ho, E. W. K. See-To, and D. K. W. Chiu, ""Price tag" of risk of using E-payment service," *Journal of Internet Commerce*, vol. 19, no. 3, pp. 324–345, 2020.
[21] F. D. Davis, "Perceived usefulness, perceived ease of use, and user acceptance of information technology," *MIS Quarterly*, vol. 13, no. 3, pp. 319–340, 1989.
[22] M. L. Ashour and R. M. Al-Qirem, "Consumer adoption of self-service technologies: integrating the behavioral perspective with the technology acceptance model," *Journal of Asian Finance, Economics and Business*, vol. 8, no. 3, pp. 1361–1369, 2021.
[23] M. I. Khan, M. A. Saleh, and A. Quazi, "Social media adoption by health professionals: a TAM-based study," *Informatics*, vol. 8, no. 1, 2021.
[24] C. H. Wang, "An intuitionistic fuzzy set-based hybrid approach to the innovative design evaluation mode for green products," *Advances in Mechanical Engineering*, vol. 8, no. 4, pp. 1–16, 2016.
[25] X. Zhang, Y. Wang, and Z. Li, "User acceptance of machine learning models-integrating several important external variables with technology acceptance model," *The International Journal of Electrical Engineering & Education*, 2021, inpress.
[26] Y. Zhong, S. Oh, and H. C. Moon, "Service transformation under industry 4.0: investigating acceptance of facial recognition payment through an extended technology acceptance model," *Technology in Society*, vol. 64, 2021.
[27] I. Benbasat and A. S. Dexter, "An investigation of the effectiveness of color and graphical information presentation under varying time constraints," *MIS Quarterly*, vol. 10, no. 1, pp. 59–83, 1986.
[28] F. D. Davis and V. Venkatesh, "A critical assessment of potential measurement biases in the technology acceptance model: three experiments," *International Journal of Human-Computer Studies*, vol. 45, no. 1, pp. 19–45, 1996.
[29] H.-P. Shih, "An empirical study on predicting user acceptance of e-shopping on the Web," *Information & Management*, vol. 41, no. 3, pp. 351–368, 2004.
[30] H. Van der Heijden, "Factors influencing the usage of websites: the case of a generic portal in The Netherlands," *Information & Management*, vol. 40, no. 6, pp. 541–549, 2003.
[31] M. T. Dishaw and D. M. Strong, "Extending the technology acceptance model with task-technology fit constructs," *Information & Management*, vol. 36, no. 1, pp. 9–21, 1999.
[32] J.-W. Moon and Y.-G. Kim, "Extending the TAM for a world-wide-web context," *Information & Management*, vol. 38, no. 4, pp. 217–230, 2001.
[33] P. J. Hu, P. Y. K. Chau, O. R. L. Sheng, and K. Y. Tam, "Examining the technology acceptance model using physician acceptance of telemedicine technology," *Journal of Management Information Systems*, vol. 16, no. 2, pp. 91–112, 1999.
[34] G. C. Bruner and A. Kumar, "Explaining consumer acceptance of handheld Internet devices," *Journal of Business Research*, vol. 58, no. 5, pp. 553–558, 2005.
[35] M. S. Featherman and P. A. Pavlou, "Predicting e-services adoption: a perceived risk facets perspective," *International Journal of Human-Computer Studies*, vol. 59, no. 4, pp. 451–474, 2003.
[36] S. F. Sönmez and A. R. Graefe, "Determining future travel behavior from past travel experience and perceptions of risk and safety," *Journal of Travel Research*, vol. 37, no. 2, pp. 171–177, 1998.
[37] J. F. Hair Jr., W. C. Black, B. J. Babin, and R. E. Anderson, *Multivariate Data Analysis: A Global Perspective*, Pearson, Upper Saddle River, NJ, USA, 7th edition, 2010.
[38] F. N. Kerlinger, *Foundation of Behavioral Research*, McGraw-Hill, New York, NY, USA, 1978.
[39] C. Fornell and D. F. Larcker, "Evaluating structural equation models with unobservable variables and measurement error," *Journal of Marketing Research*, vol. 18, no. 1, pp. 39–50, 1981.
[40] E. G. Carmines and J. P. MacIver, "Analyzing models with unobserved variables: analysis of covariance structures," in *Social Measurement*, G. W. Bohrnstedt and E. F. Borgatta, Eds., pp. 65–115, Sage, Beverly Hills, CF, USA, 1981.
[41] R. P. Bagozzi and Y. Yi, "On the evaluation of structural equation models," *Journal of the Academy of Marketing Science*, vol. 16, no. 1, pp. 74–94, 1988.
[42] K. G. Jöreskog and D. Sörbom, *LISREL 8: User's Reference Guide*, Scientific Software International, Chicago, IL, USA, 1996.
[43] C. Forza and R. Filippini, "TQM impact on quality conformance and customer satisfaction: a causal model," *International Journal of Production Economics*, vol. 55, no. 1, pp. 1–20, 1998.
[44] E. Hair, T. Halle, E. Terry-Humen, B. Lavelle, and J. Calkins, "Children's school readiness in the ECLS-K: predictions to academic, health, and social outcomes in first grade," *Early Childhood Research Quarterly*, vol. 21, no. 4, pp. 431–454, 2006.
[45] M. W. Brown and R. Cudeck, "Alternative ways of assessing model fit," *Testing Structural Equation Models*, vol. 154, pp. 136–162, 1993.
[46] P. Y. K. Chau and P. J.-H. Hu, "Information technology acceptance by individual professionals: a model comparison approach," *Decision Sciences*, vol. 32, no. 4, pp. 699–719, 2001.

Hindawi
Mathematical Problems in Engineering
Volume 2021, Article ID 7572818, 18 pages
https://doi.org/10.1155/2021/7572818

Research Article

Establishing an AI Model on Data Sensing and Prediction for Smart Home Environment Control Based on LabVIEW

Kai-Chao Yao, Wei-Tzer Huang, Cheng-Chun Wu, and Teng-Yu Chen

Department of Industrial Education and Technology, National Changhua University of Education, No. 2 Shi-Da Road, Changhua City, Taiwan

Correspondence should be addressed to Kai-Chao Yao; kcyao@cc.ncue.edu.tw and Wei-Tzer Huang; vichuang@cc.ncue.edu.tw

Received 31 May 2021; Accepted 6 July 2021; Published 22 July 2021

Academic Editor: Kim-Hua Tan

In this study, the authors aimed to realize a smart home using an AI model that can be integrated with the Laboratory Virtual Instrument Engineering Workbench (LabVIEW) application to realize environment control. The collected input data were outdoor temperature, indoor temperature, humidity, illumination, and indoor person count. The output control decisions included control of air conditioners, dehumidifiers, power curtains, and lights. An artificial neural network was utilized to process the input data for machine learning for the objective of achieving a comfortable environment. In addition, the control decision predictions made by this AI model were analyzed for model loss and model accuracy. This study implemented the model. Specifically, LabVIEW was used to design the sensing component, data display, and control interface, and Python was used to establish the intelligent model. Moreover, by using the web publishing tool built into LabVIEW, remote sensing and control were fulfilled in this implementation.

1. Introduction

Common household items can be transformed into smart devices through sensors. This idea inspires the use of AI models to overcome the problems associated with controlling various appliances in smart homes. With the development of the social economy and the rapid increase in the variety of people's needs, many appliances can be found in a typical household. However, it remains difficult to manage and control these appliances, while fulfilling households' needs for comfort, health, energy reduction, and security, through, for example, automatic temperature control and security over the control of devices. When such appliances use artificial intelligence to realize remote and environmentally aware automated control, user comfort is improved significantly [1–3]. A few scientific works [4, 5] have described the development of "smart homes" through machine learning technologies, and some of the practical implementations of this idea, such as that by Salhi, use machine learning algorithms to realize the early detection of gas leakage and for the control of appliances in smart homes. Casaccia proposed a system composed of domestic sensors and machine learning algorithms to measure users' well-being.

The Internet of Things uses multiple sensors to detect temperature, light, sound, and motion, all of which act as different data sources. Because massive amounts of data are involved, machine learning can be applied to existing home automation systems to significantly enhance their performance. The deployment of IoT and the utilization of AI models should be advanced to usher in a new era of smart home development [6–8].

The most commonly used AI algorithms are artificial neural networks (ANNs), recurrent neural networks (RNNs), and long short-term memory (LSTM). In [9–11], the ANN was used to analyze sensor data and output control decisions. In [12–14], the RNN was used to analyze the behavior of buildings, such as abnormality detection and energy consumption measurement. LSTM applies to IoT data analysis for living activity sensing system any household appliance control can been in [15–17]. Various AI models are widely used in different smart house or building applications. However, the manner in which such models can be practically deployed in the Laboratory Virtual Instrument Engineering Workbench (LabVIEW) software environment has not been discussed in these studies.

In [18], LabVIEW was used in conjunction with IoT technology to establish a smart home. LabVIEW is used to create virtual instruments and develop control schemes with faster development times, lower costs, and greater flexibility compared with traditional instruments and control schemes. Python is the most convenient and effective tool for importing AI algorithms. Bhoi applied Python to design a fire detection system for smart homes, and Nadaf designed a smart mirror by using Raspberry Pi for human monitoring and intrusion detection [19, 20]. In the present study, LabVIEW was used along with Python to build smart devices. These two software packages were used collaboratively to manage the programming aspects of data collection, AI model establishment, and control algorithm development. The proposed deployment can be used to develop AI applications pertaining to data sensing and prediction for controlling smart home environments.

2. Preliminaries

2.1. Smart Space Monitoring and Control Based on IoT and LabVIEW. In [18, 21], the authors aimed to build a smart home system and a museum display cabinet with remote monitoring and control. NI myRIO was used as the control unit to create a control function for smart systems, and LabVIEW was used to realize the wireless transmission function in a program designed to run on NI myRIO. The system was capable of detecting each sensor wirelessly. A shared variable function and a built-in web publishing tool were used to construct the remote control function, which was used to control and monitor data immediately on a local PC or a remote tablet. Moreover, the system was capable of activating various relays for the control of, for example, alerts, air conditioning, lights, and powered windows.

2.2. AI Models. An ANN is a computing system inspired by the human nervous system. It is based on theories of massive interconnections and the parallel processing architecture of the biological system. An ANN model is a data-driven mathematical model that can solve problems through machine learning neurons. One of the advantages of ANNs is their capability to identify complex nonlinear relationships between inputs and outputs without using inputs in the form of direct knowledge or physical processes. The most common type of ANNs comprises three layers, namely, an input layer, a hidden layer, and an output layer. Figure 1 illustrates the architecture of a typical ANN [22].

3. System Structure

Figure 2 shows the system structure of data sensing and control prediction for the smart home environment. LabVIEW is used as the graphical user interface (GUI). Python is used to construct an ANN AI model that is embedded in LabVIEW for data analysis and prediction. LabVIEW is responsible for sensor data acquisition, including data on temperature, illuminance, humidity, and the number of people present indoors. In addition, LabVIEW is used to achieve control ability through an NI DAQ.

Once the system is completed, the features of this system module can be integrated into a patrol robot system, such as the robot constructed in [23] to convert it into an Artificial Intelligence of Things (AIoT) smart home robot. Figure 3 shows the structure of an AIoT patrol robot.

4. Main Results

In this study, the user interface design for integrating an AI data sensing and prediction model for smart home environment control was constructed using LabVIEW. The monitoring and control interface is shown in Figure 4. The human–machine interface design includes a (A) user login block, (B) sensor data block, (C) environmental monitoring block, (D) environmental prediction block, and (E) AI mode selection block. Moreover, the LabVIEW Python node that is embedded in LabVIEW is connected to the AI model that must be trained and tested for predicting actual control commands in the household environment. By following this method, the AI model can be constructed as a complex ANN that can generate predictions and perform intelligent control. Furthermore, the features of LabVIEW can aid in the creation of GUIs for analysis and monitoring. Figure 5 shows a block diagram of the smart home environment control system. Figure 6 shows the function block of the NI Python node.

This proposed system is designed to be able to integrate various AI models. These AI models can be selected in the human–machine interface block E. The AI model used in this study is the ANN. Block E can reproduce the detected data, reset the data, pause detection, select an AI model, and display the predicted sensing values. Figure 7 shows block E in the smart home environment control interface. Figure 8 shows the part of the block diagram pertaining to the integration of the embedded AI model in LabVIEW.

4.1. Sign-In Function. For system security, identity verification is deployed before the operating system, as illustrated in block A of Figure 4. If the login process fails, the monitoring system cannot be entered. Figure 9 and Figure 10 depict images of system login success and failure, respectively.

4.2. Environment Sensing and Control. In the environmental monitoring part, the human–machine interface displays the real-time environmental condition data captured using sensors. Block B in Figure 3 depicts the real-time data captured by the sensors, including the current number of people and the current temperature, humidity, and illuminance. Block C in Figure 3 represents the display data converted into suitable units, as illustrated in Figure 11. Figure 12 presents a partial program diagram of the environmental monitoring and control, and Figure 13 depicts a circuit diagram of the designed sensing data acquisition

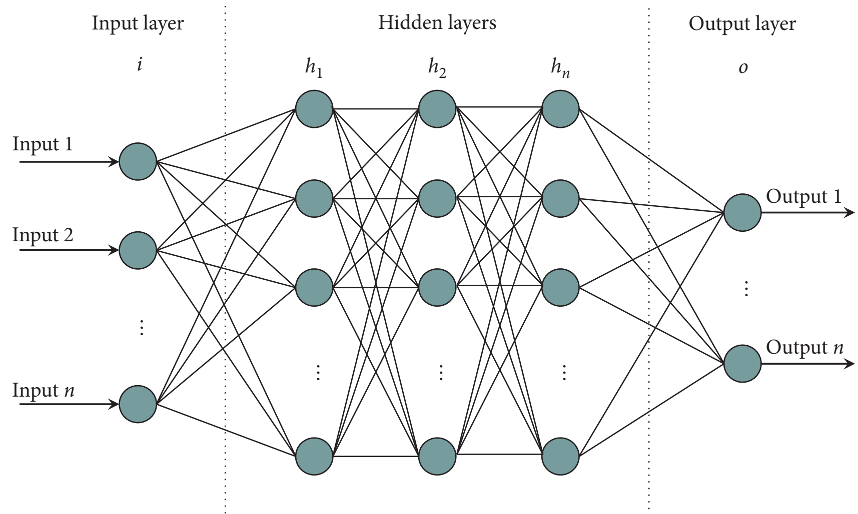


Figure 1: Schematic of the architecture of a typical artificial neural network.

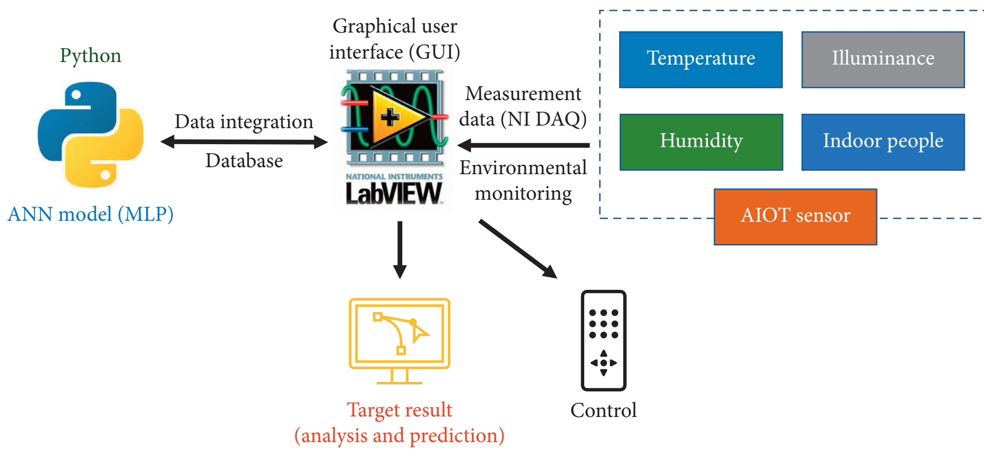


Figure 2: System structure of data sensing and control prediction for smart home environment.

system. The acquired sensing data are sent to the AI model constructed using Python, and the predictions of the AI model are used for home appliance control. On the control device, an NI-DAQmax is used to output the control signals and perform remote relay on-off control.

4.3. Real-Time Data Collection and Prediction. In Section 4.2, the ANN-based AI model constructed using Python was described. This human–machine interface system was designed to facilitate the addition of different AI models for integration. Figure 14 shows the data predicted by the trained ANN model by using the person count, temperature, humidity, and illuminance data captured in Section 4.2. In the human–machine interface in Figure 3, these data are shown in block D. Figure 15 depicts the part of the program diagram for real-time data processing and data prediction.

4.4. AI Model and Learning. In this study, we used Python to construct the AI model depicted in Figure 16, and we used machine learning techniques to predict environmental conditions. Machine learning is a part of artificial intelligence. To facilitate efficient and effective learning by the AI model, the learning process is generally divided into two steps: training and testing. In the training step, historical data, comprising features, and labels are used. After the AI model process testing, it can output its predictions. The AI learning model is analogous to the brain of an artificial intelligence system. If one desires to achieve a more intelligent machine, one must construct a neural network model that is trained under greater complexity. The construction process is depicted in Figure 17. In this study, we used a supervised learning method to establish the ANN and to input standardized features and labels for training and learning. In the process, the AI model is repeatedly trained and adjusted to achieve high speed and high prediction accuracy.

The learning model developed in this study uses an ANN to realize environmental prediction. The ANN contains many neurons, some of which are responsible for receiving data and others for transmitting data. It is an adaptive Internet network, and its structure can be represented using a

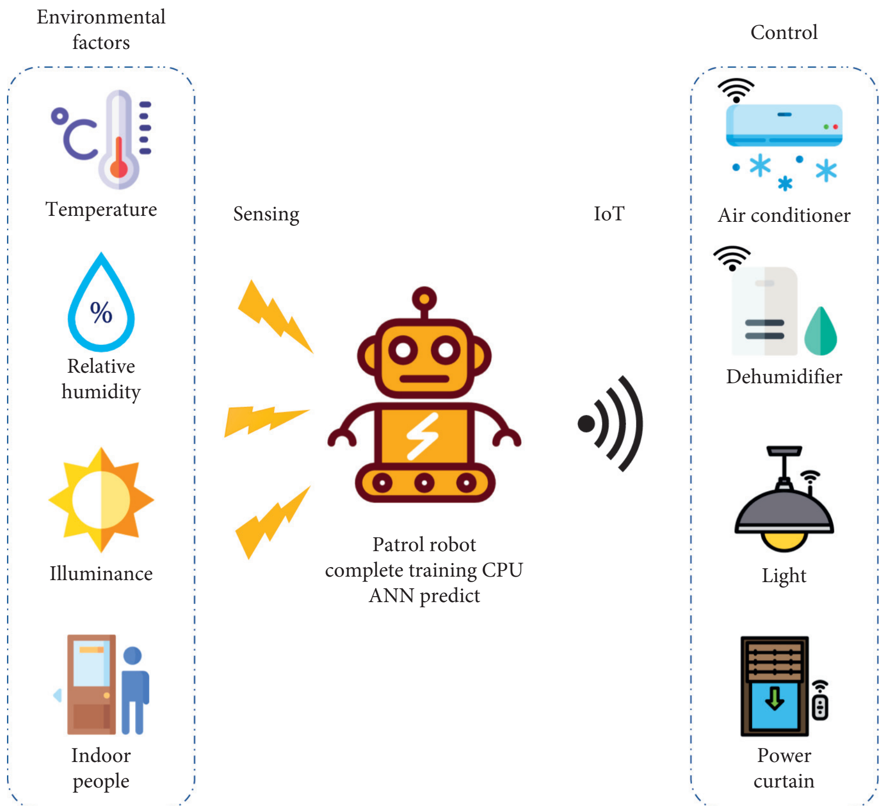


Figure 3: Structure of an AIoT patrol robot.

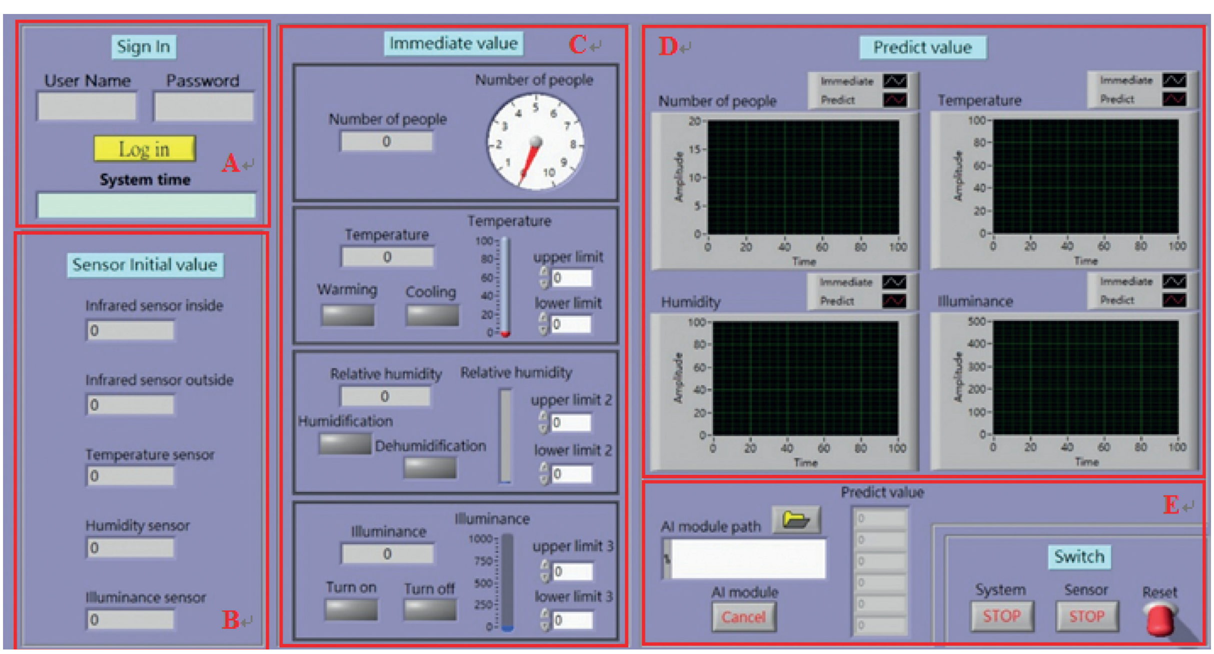


Figure 4: Monitoring and control interface for smart home environment control.

simple neuron model, such as the M-P neuron model depicted in Figure 18.

In an M-P model, a certain neuron may receive multiple input signals simultaneously, as shown in Figure 18. Because biological neurons have different synaptic properties and synaptic strengths, they have different effects on neurons. They can be represented by the weights $\omega_{1\ldots}\omega_{i\ldots}\omega_n\omega$, and their positive and negative values denote prominent

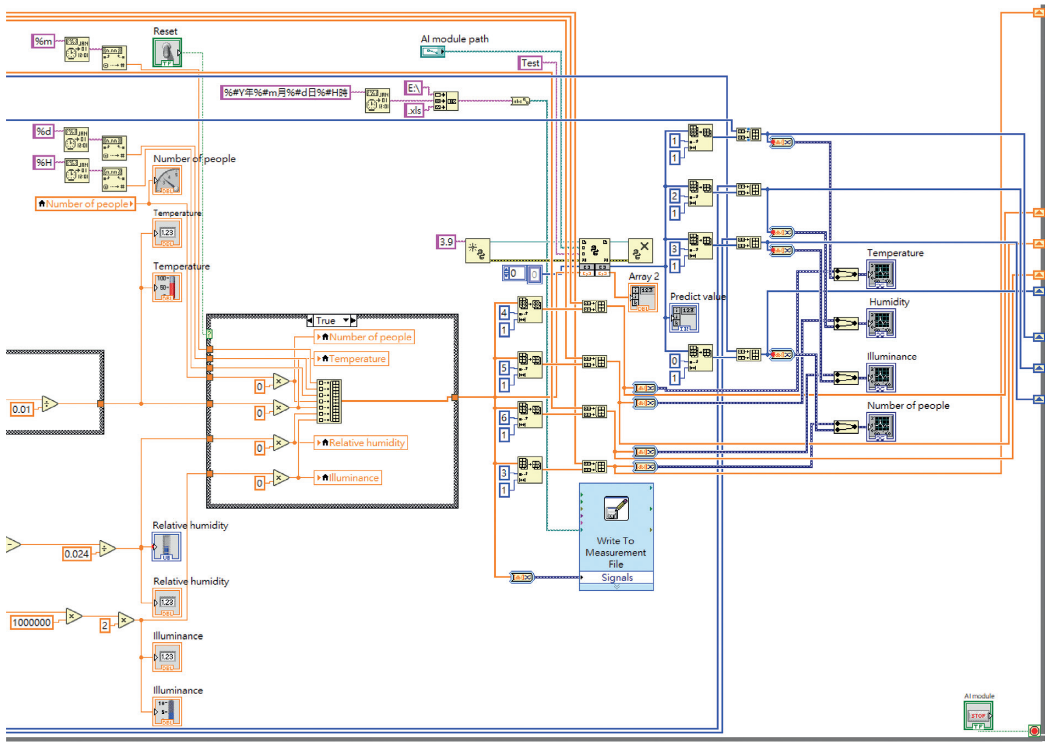


FIGURE 5: Block diagram of the smart home environment control system.

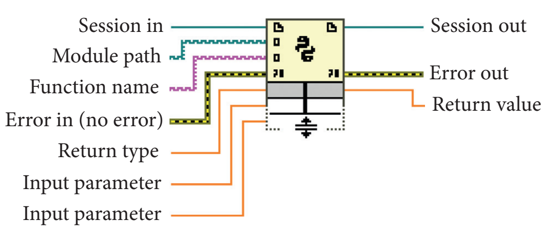


FIGURE 6: Function block of NI Python node.

excitement and inhibition in biological neurons, respectively. The magnitudes of prominent excitement and inhibition represent the different strengths of the prominent connections. To express a threshold θ (threshold), also called a bias (bias), neurons have two states: excited and inhibited. Under normal circumstances, most neurons are in an inhibited state. However, when a neuron is stimulated and its potential exceeds a threshold (θ), the neuron is activated and excited, and it subsequently transmits chemical substances, that is, information, to other neurons. The associated data processing flow is represented by the mathematical model expressed in the following equation:

$$y = f\left(\sum_{i=0}^{n} \omega_i x_i - \theta\right). \quad (1)$$

The M-P model shown in Figure 18 adjusts the weight assigned to each input value during the machine learning process and forms an intelligent model by adjusting the weight ω or the threshold θ. The greater the signal value entering a neuron, the easier it is to trigger neurons and the greater is the influence on the operation of the neural network. Conversely, the smaller the signal value, the weaker is the effect. If the signal is too small, it can even be ignored for computational savings and smaller errors in the output value. The output value is adjusted and converted using an activation function. As depicted in Figure 19, Python is applied to construct the M-P model and the activation function uses a function formulated in terms of tan$h$. To improve the accuracy of learning, the neural network is developed as a multilayer perceptron with multiple hidden layers (Figure 20). Figure 21 shows the setting of the activation function during the establishment of the MLP in this study. The rectified linear unit (ReLU) function is used as the activation function after the calculated input value is normalized. Furthermore, the model standardizes its output value ranges and the relationship between the output values. Figure 19 depicts the ANN-MLP model used in this study. Figure 22 depicts the architecture of the ANN-MLP model.

Tables 1 and 2 summarize parts of the training and testing datasets used in the training and testing processes, respectively.

By using the learning data summarized in Table 1, one can obtain an AI model with predictive capabilities. This AI model must be verified and evaluated to understand its predictive performance in actual use. To this end, the simplest method involves the use of a new set of input data for testing, as summarized in Table 2. The loss function can be obtained during the verification process. When the value of the loss function is small, the prediction model works well. Conversely, when the value of the loss function is large, the

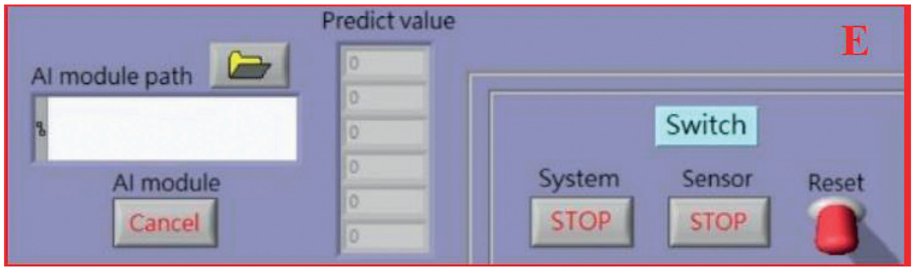


Figure 7: Block E in the smart home environment control interface.

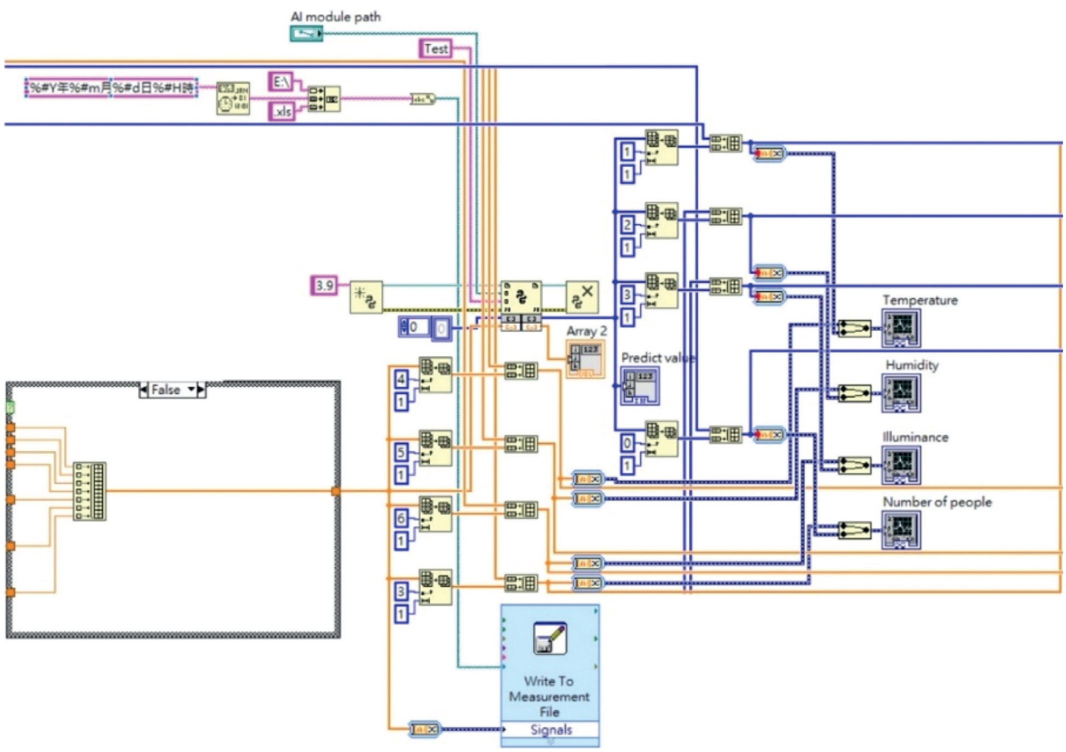


Figure 8: The block diagram pertaining to the integration of the embedded AI model.

model does not perform as expected and the weighting parameters must be adjusted to achieve the desired performance. Figure 23 depicts a flowchart of the verification and evaluation steps of the learning model. The steps for verifying the model are as follows:

Step 1: prepare the learning dataset

Step 2: separate the training and test data into input data and output data

Step 3: input the training data into the neural network for training

Step 4: compare the training results of the neural network with the testing output data to observe the loss function for verification

Step 5: feedback the comparison difference in Step 4 and adjust the weight parameters

Step 6: update the neural network parameters (back to Step 3)

After the fourth step, the feedback weighting parameter adjustment module in the machine learning algorithm is executed to adjust the model for obtaining more accurate predictions and improved judgment abilities. The neural network can modify the weighting parameter in terms of the loss function to reduce the error to achieve more accurate predictions. Some commonly used indicators are the mean squared error (MSE) and cross entropy error (CEE). In statistics, the MSE is expressed in terms of an estimated function, T, for an unobservable population number θ. The following equation expresses the definition of the MSE:

$$\mathrm{MSE}(T) = E\left((T-\theta)^2\right). \tag{2}$$

The MSE is the expected value of the error squared. The error is the difference between the estimated value and the estimated quantity. MSE satisfies the following equation:

$$\mathrm{MSE}(T) = \mathrm{var}(T) + (\mathrm{bias}(T))^2. \tag{3}$$

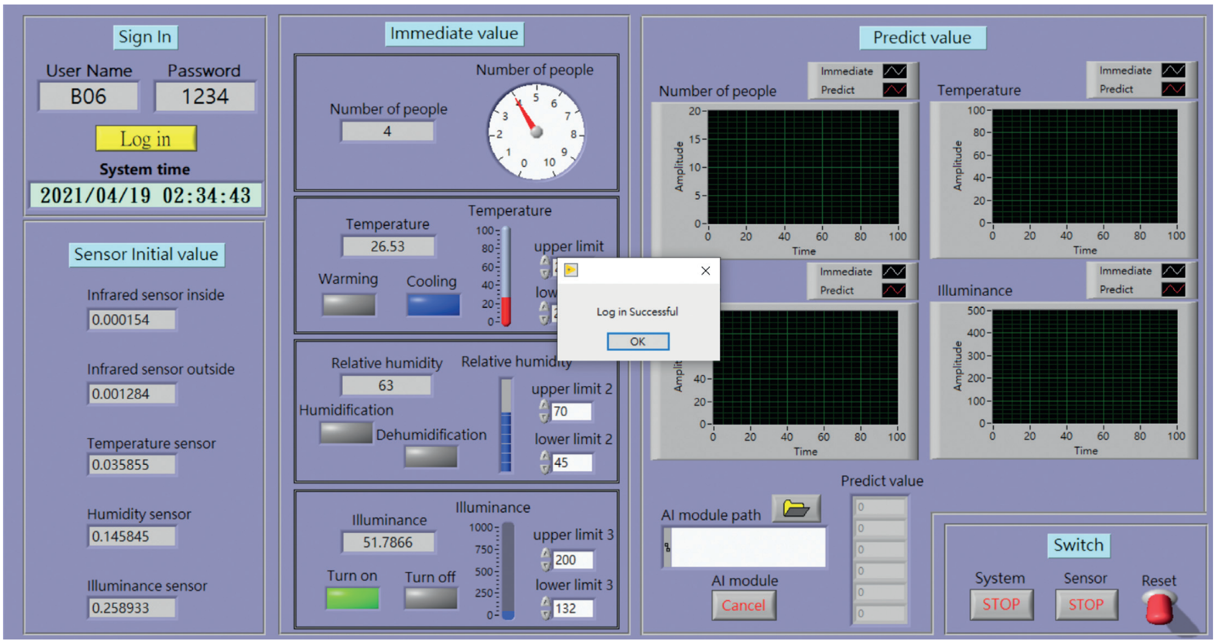


Figure 9: Successful system login.

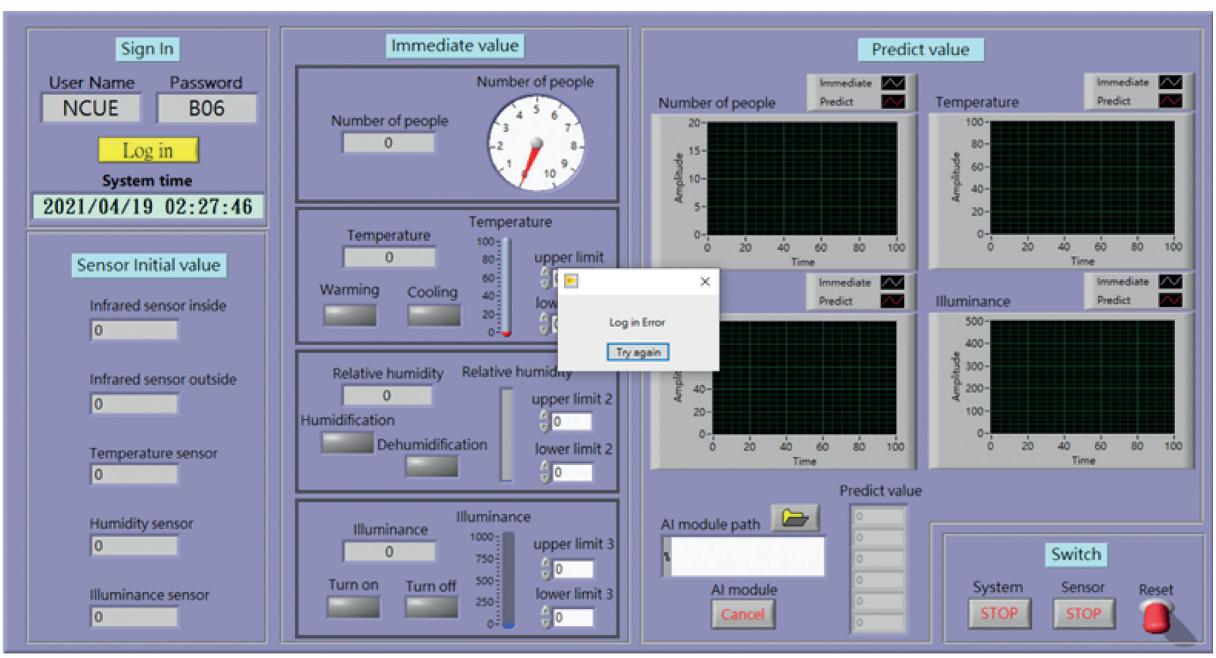


Figure 10: System login failure.

Among them, the bias (T) is the difference between the expected value of the estimated function and the unobservable population number, similar to the threshold θ or the bias of neuron activity, which satisfies the following equation:

$$\text{bias}(T) = E(T) - \theta. \tag{4}$$

In this study, model loss is verified by using the MSE function. Moreover, the backpropagation method is used to adjust and modify the model. The respective mathematical expressions are given in the following equations:

$$\text{MSE} = \frac{\sum_{i=1}^{k} |y_i - t_i|}{k}, \tag{5}$$

$$L(E) = \frac{1}{2}\sum_{k}(y_k - t_k)^2. \tag{6}$$

In equations (5) and (6), y denotes the output data or the prediction result of the machine learning algorithm, and t denotes the correct solution data. The loss of the training output function and a dataset with the correct data can be

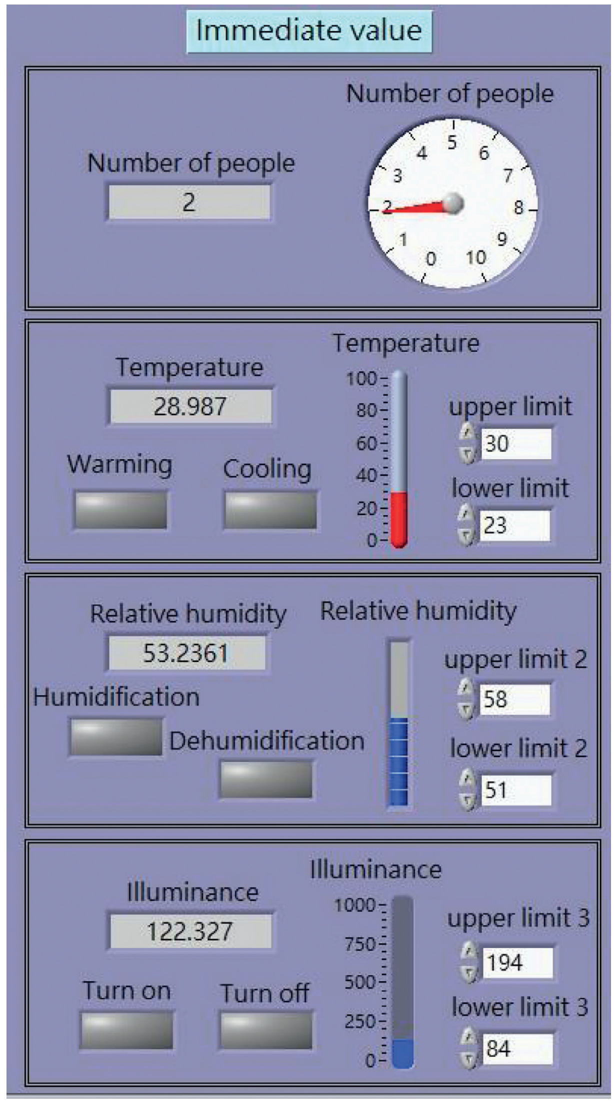


Figure 11: Display of environmental monitoring data.

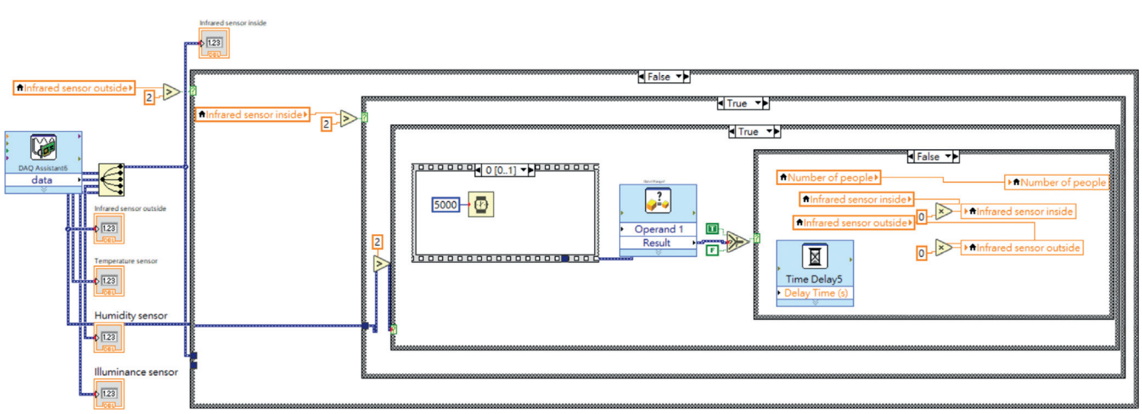


Figure 12: The program diagram pertaining to environmental monitoring and control.

used to verify the process. By taking the difference and summing the square values of these differences, we can obtain the mean square error. This value is used as the difference loss judgment of the data, and it is used to implement feedback correction. If the loss is decreasing, a better model can be obtained. Figure 24 depicts a model loss comparison diagram between the model after training and that after testing. In this figure, the training and testing losses

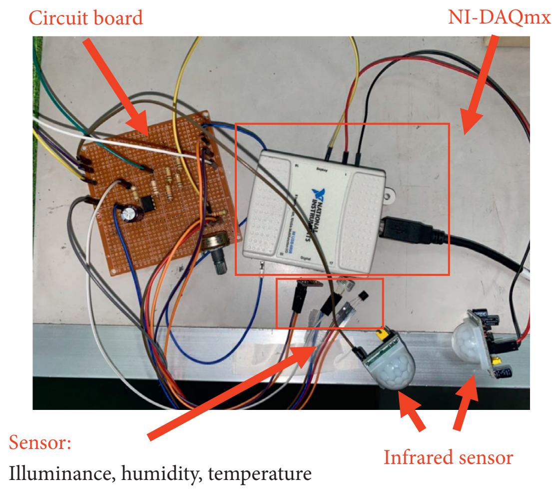


Figure 13: Designed sensing data acquisition circuit.

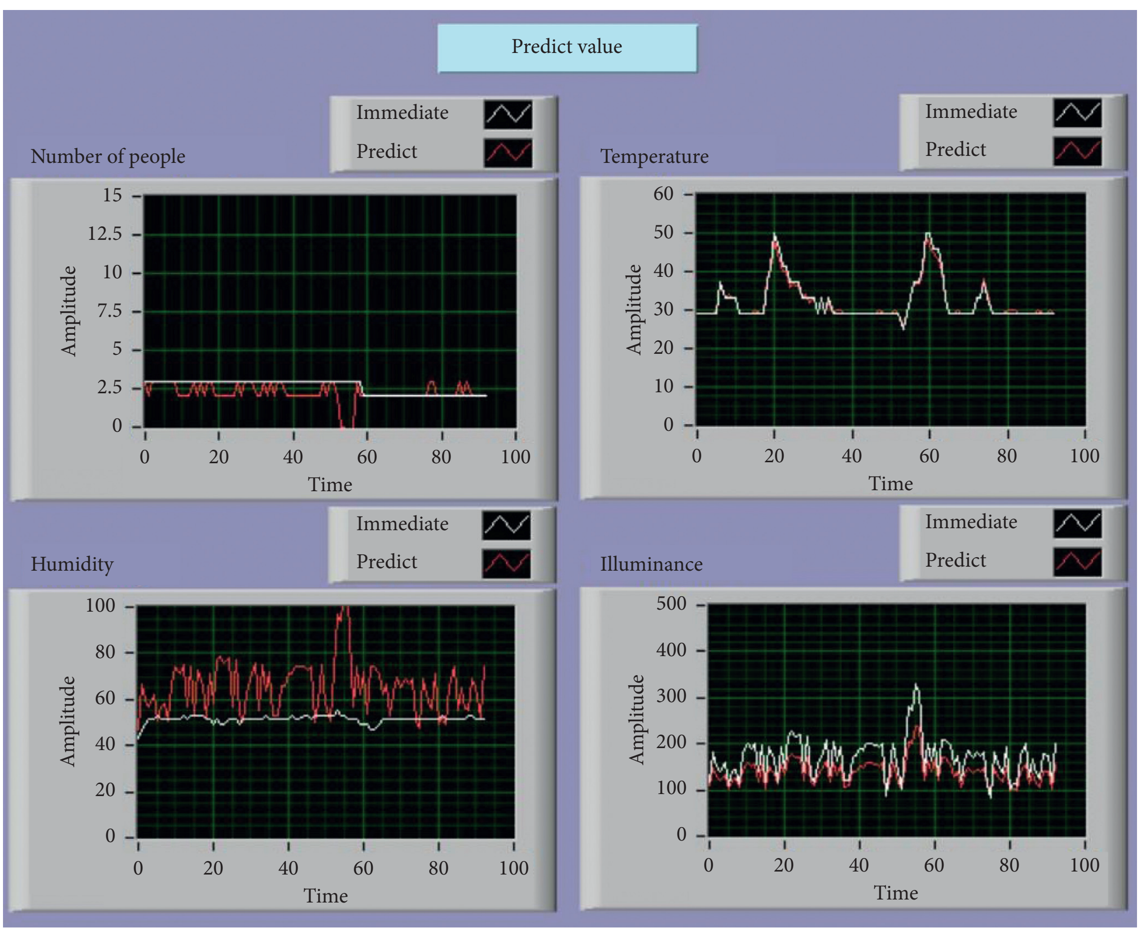


Figure 14: Comparison of real-time and predicted data.

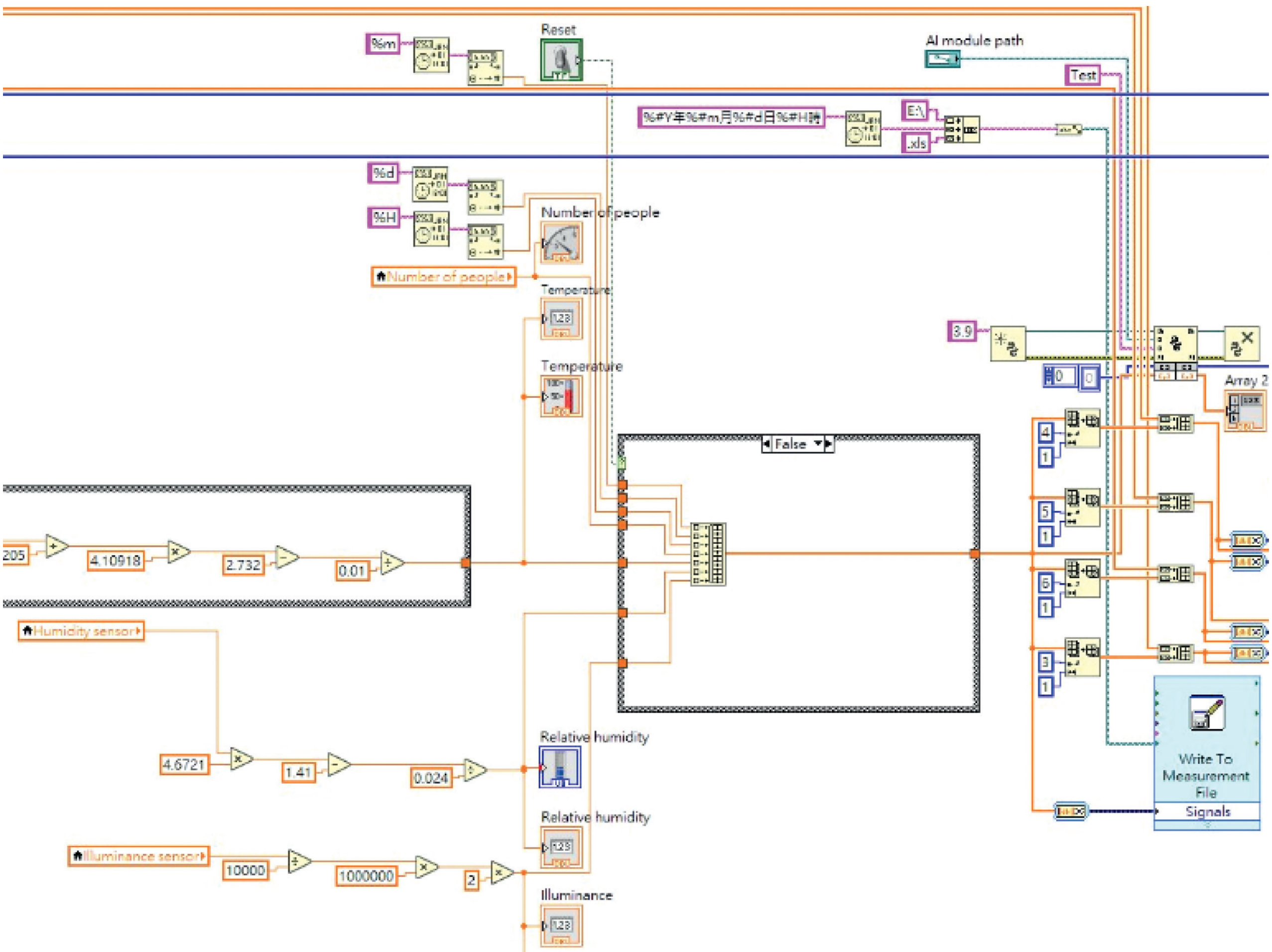


Figure 15: The program diagram pertaining to real-time processing and data prediction.

```
Model: "sequential"
_________________________________________________________________
Layer (type)                 Output Shape              Param #
=================================================================
dense (Dense)                (None, 50)                400
_________________________________________________________________
dense_1 (Dense)              (None, 50)                2550
_________________________________________________________________
dense_2 (Dense)              (None, 4)                 204
=================================================================
Total params: 3,154
Trainable params: 3,154
Non-trainable params: 0
_________________________________________________________________
```

Figure 16: Establishment of AI model in Python.

exhibit decreasing trends, which indicates that the training results are reasonable.

In Figure 24, after 25 training runs, although the model verification loss tends to decrease, database normalization must be considered when processing a large quantity of data. Figures 25 and 26 show whether the data in the database are standardized. The difference graph of the loss function can be obtained after 100 runs of posttraining.

When much data are collected, complex neural networks must use appropriate algorithms for data processing. Gradient descent is one such suitable algorithm. This method can be used to identify the errors in neural networks.

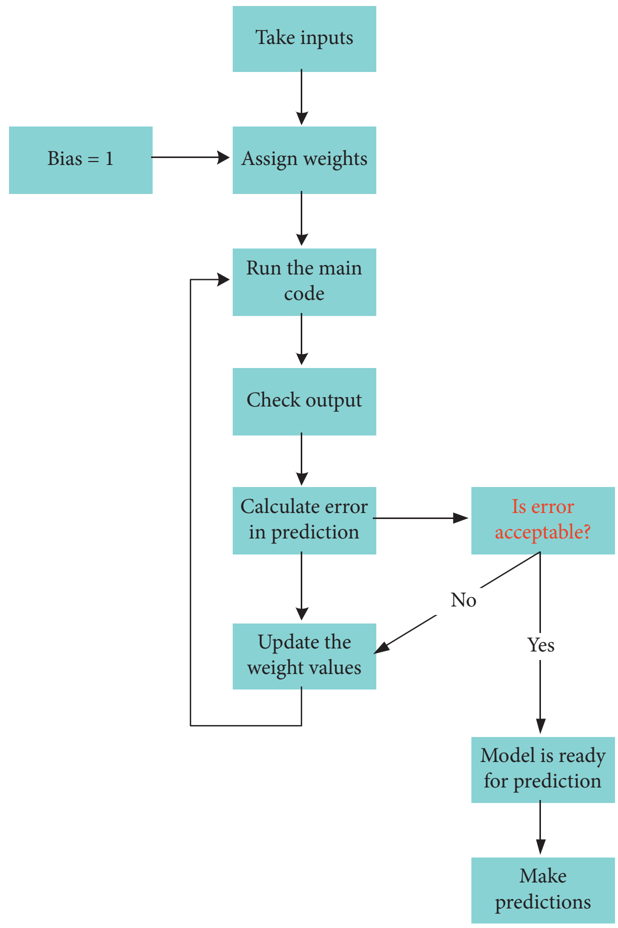


FIGURE 17: Flowchart of ANN design.

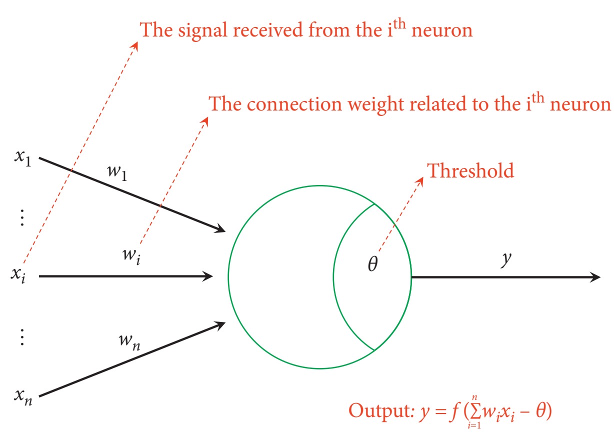


FIGURE 18: Diagram of the (ANN) M-P model.

Figure 27 shows the graph of model loss with 10,000 data points as inputs. Many types of gradient descent methods can be used to adjust the weights. In this study, we used the stochastic gradient descent (SGD) method to determine the gradient of the weighting parameters. This method can update the weight, ω, in the direction of the gradient. Specifically, L is the loss function, η is the learning rate, and $\partial_L/\partial_\omega$ is the gradient of the loss function with respect to weight. The mathematical equation is as follows:

$$\begin{aligned} \omega_1 &= \omega_0 - \eta \frac{\partial_L}{\partial_{\omega_0}}, \\ \omega_2 &= \omega_1 - \eta \frac{\partial_L}{\partial_{\omega_1}}, \\ &\vdots \quad \vdots \,. \end{aligned} \tag{7}$$

In the preceding verification model, the training process endows the model with its prediction ability. If perfect

```python
class NeuralNetwork:

    def __init__(self, layers, activation='tanh'):
        if activation == 'logistic':
            self.activation = logistics
            self.activation_deriv = logistics_derivative
        elif activation == 'tanh':
            self.activation = tanh
            self.activation_deriv = tanh_deriv

        self.weight = []
        for i in range(1, len(layers) - 1):
            self.weight.append((2 * np.random.random((layers[i - 1] + 1, layers[i] + 1)) - 1) * 0.25)
            self.weight.append((2 * np.random.random((layers[i] + 1, layers[i + 1])) - 1) * 0.25)
```

Figure 19: (ANN) M-P model program construction process.

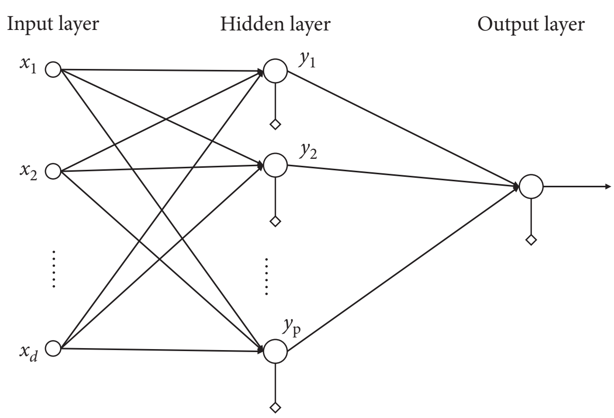


Figure 20: Schematic of the ANN-MLP model.

```python
#Creative model structure
model = tf.keras.models.Sequential()
model.add(tf.keras.layers.Dense(units = 50,                     # Add hidden layer 1
                                activation = tf.nn.relu,
                                kernel_regularizer=tf.keras.regularizers.l2(l=0.001),
                                bias_regularizer=tf.keras.regularizers.l2(l=0.001),
                                input_dim = 7))
model.add(tf.keras.layers.Dense(units = 50,                     # Add hidden layer 2
                                activation = tf.nn.relu,
                                kernel_regularizer=tf.keras.regularizers.l2(l=0.001),
                                bias_regularizer=tf.keras.regularizers.l2(l=0.001)
                                ))
model.add(tf.keras.layers.Dense(units = 4))
```

Figure 21: ANN-MLP model activation function setting.

prediction is excessively pursued in the training process, the obtained weighting parameters will cause overfitting and lead to poor actual predictions. In the simulation, model loss between the training and testing processes can be observed. This is normal. Therefore, regularization is applied to maintain the existing features and reduce the influence of a few unimportant features. The trained model should not overly rely on the weight loss during training. The revised mathematical function is expressed as in the following equation:

$$L(E) = \frac{1}{2}\sum_{k}(y_k - t_k)^2 + \lambda \sum (\omega_i), \tag{8}$$

where λ represents the choice between the prediction error and the weight term. When λ is larger, the model focuses less on the prediction gap. According to equation (8), which is used for regularization, the model loss between training and testing approaches zero, as illustrated in Figures 28 and 29.

After modification of the training model, the accuracy rate can reach 95%, as illustrated in Figure 30. The following

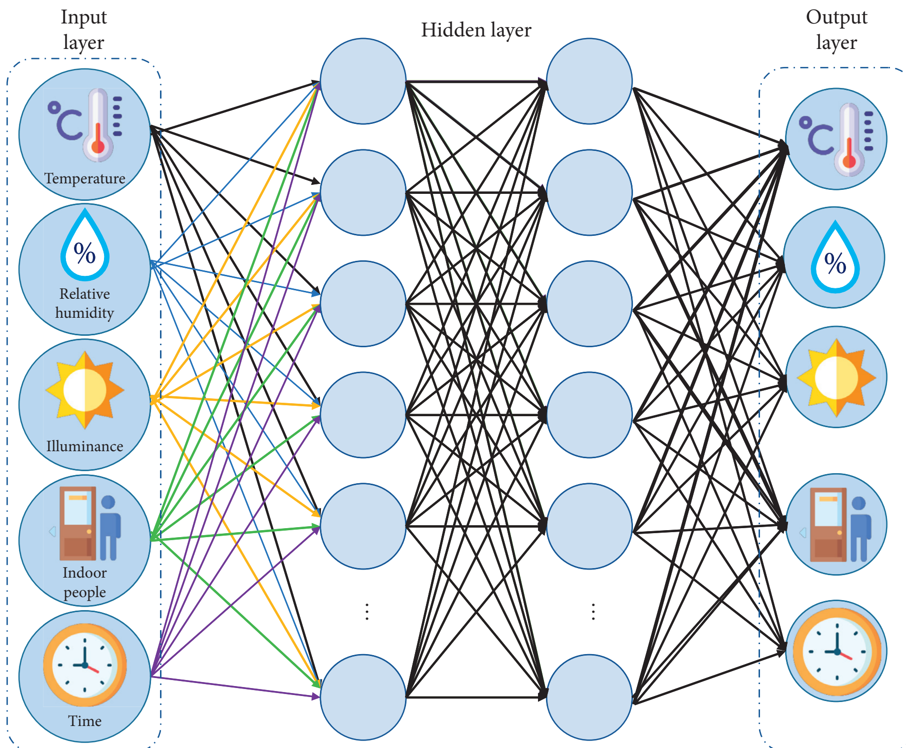


Figure 22: ANN-MLP model architecture.

Table 1: Part of the training data recorded between 2001 and 2018.

	Input data					Output data				
Day	Time	Temperature	Humidity	People	Illumination	Time	Temperature	Humidity	People	Illumination
1/1	1:00	14	60	2	95	2:00	16.7	81	4	115
1/1	12:00	13.7	63	4	115	13:00	16.4	81	4	117
1/3	23:00	13.4	65	4	117	24:00	15.9	82	0	18
1/1	4:00	13.7	62	0	18	5:00	15.3	85	0	18
1/2	7:00	12.4	67	0	18	8:00	15.6	83	1	87
1/4	9:00	11.6	71	1	87	10:00	15.8	84	1	89

Table 2: Part of the testing data recorded between 2019 and 2020.

	Input data					Output data				
Day	Time	Temperature	Humidity	People	Illumination	Time	Temperature	Humidity	People	Illumination
1/1	1:00	16.9	80	4	117	2:00	16.7	81	4	119
1/1	2:00	16.7	81	4	119	3:00	16.4	81	4	116
1/1	3:00	16.4	81	4	116	4:00	15.9	82	2	95
1/1	4:00	15.9	82	2	95	5:00	15.3	85	0	18
1/1	5:00	15.3	85	0	18	6:00	15.6	83	0	17
1/1	6:00	15.6	83	0	17	7:00	15.8	84	0	17

figures depict the real-time status and prediction status, respectively, of temperature, humidity, illuminance, and person count. In these figures, the actuality and predict lines denote the actual and the forecast situations, respectively. Figure 31 depicts 24 h real-time relative humidity and the forecast state diagram. Figure 32 depicts the real-time relative humidity and forecast state diagram for a week. Figure 33 illustrates the 24 h real-time temperature and predicted state diagram. Figure 34 presents the real-time temperature and predicted state for a week. Figure 35 depicts the real-time illuminance and forecast state diagram for a week. Figure 36 depicts the real-time person count for a week and the forecast state diagram.

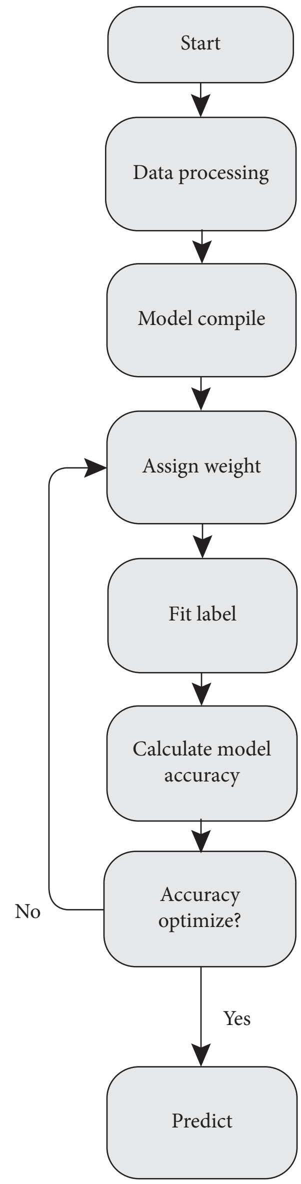


Figure 23: Flowchart of verification and evaluation steps of the learning model.

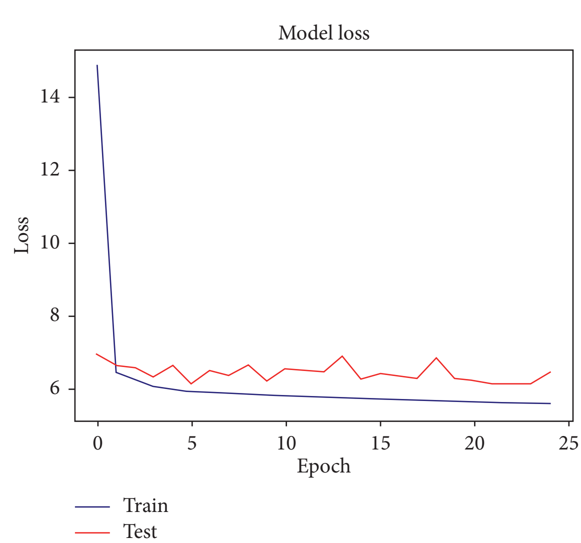


Figure 24: Comparison of model loss between model training and testing.

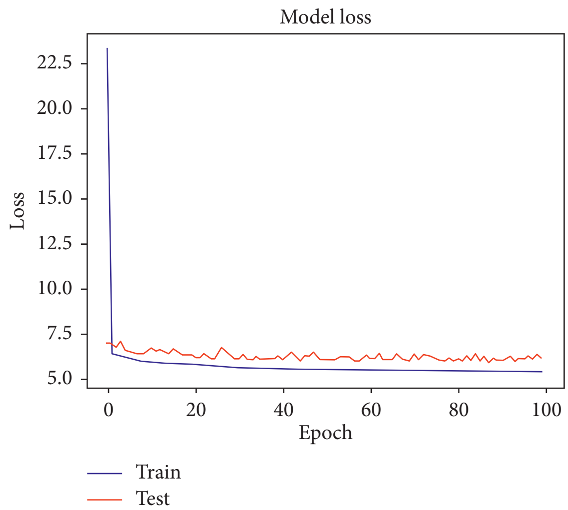


FIGURE 25: Model loss without standard database data.

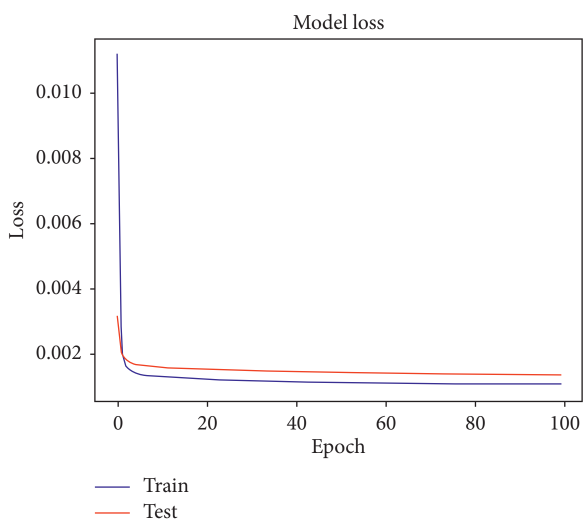


FIGURE 26: Model loss with standard database data.

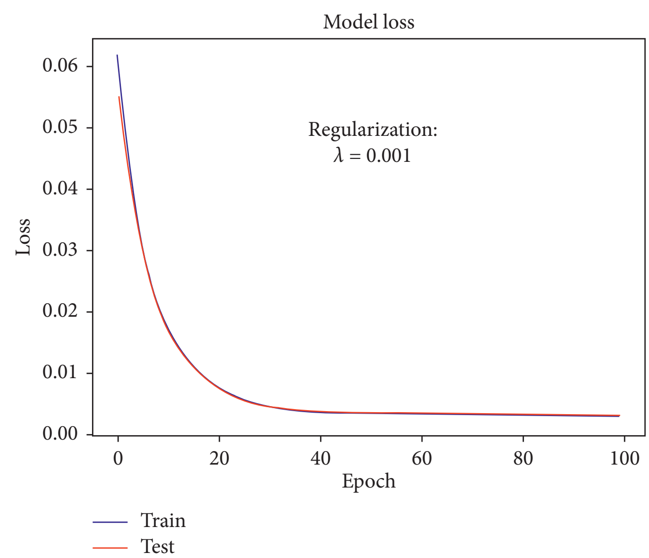


FIGURE 28: Model loss after normalization $\lambda = 0.001$.

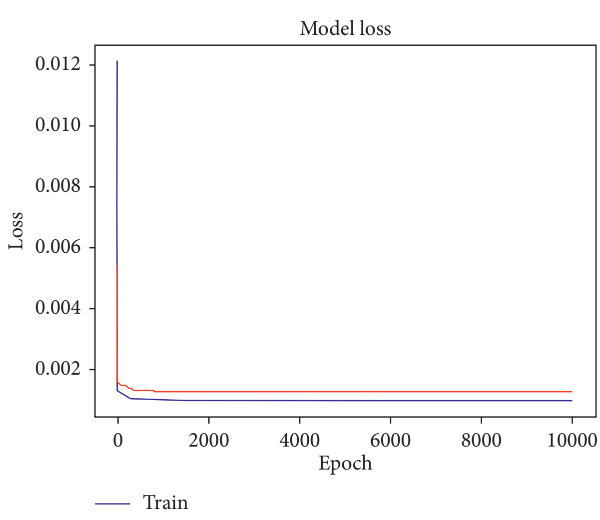


FIGURE 27: Model loss of training and testing after 10,000 data inputs.

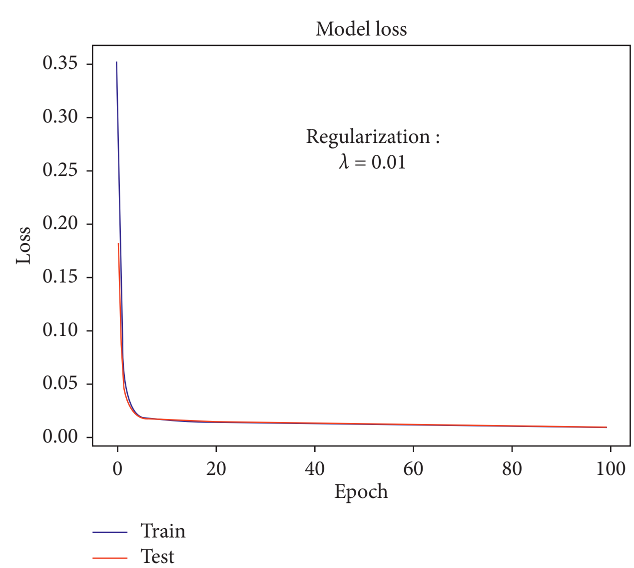


FIGURE 29: Model loss after $\lambda = 0.01$.

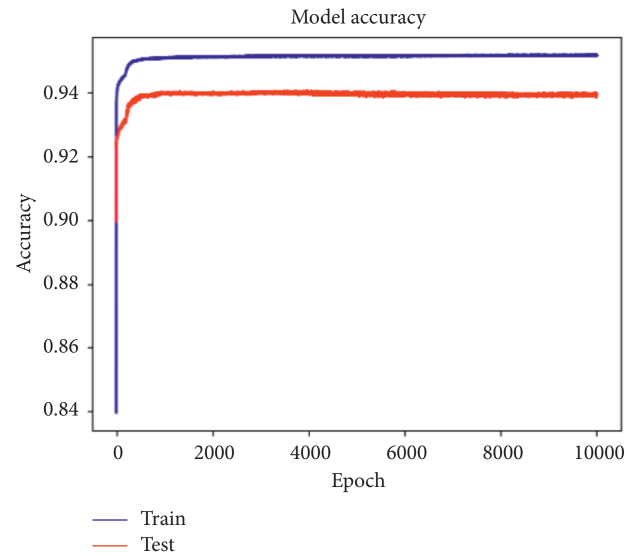


FIGURE 30: State diagram of model accuracy for model training and testing.

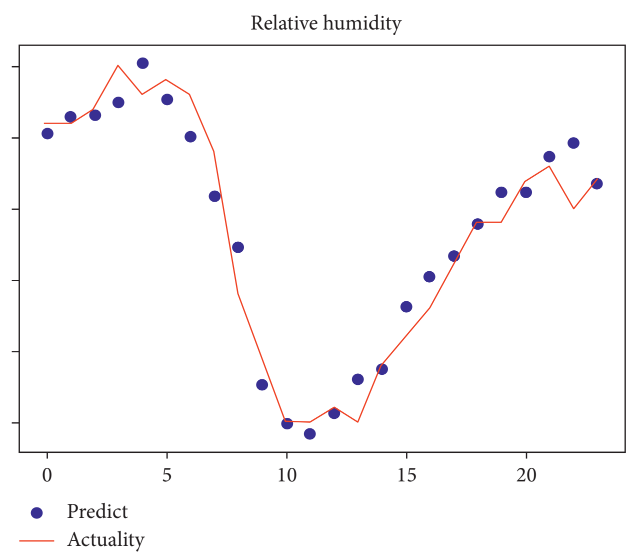


FIGURE 31: 24 h real-time humidity and forecast state diagram.

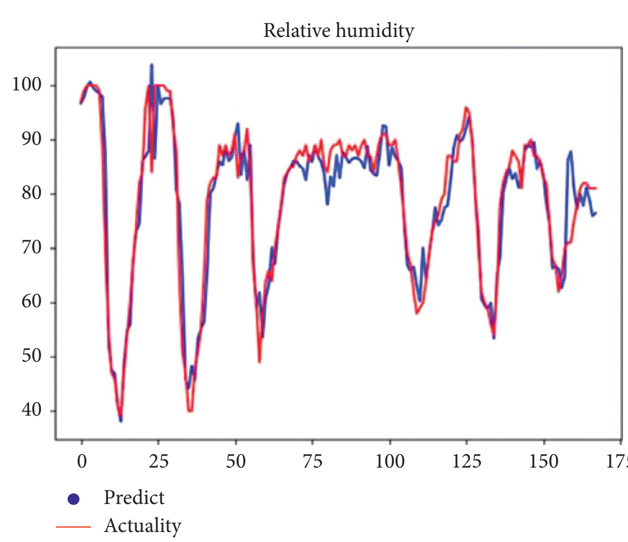


FIGURE 32: Real-time relative humidity and forecast state diagram for a week.

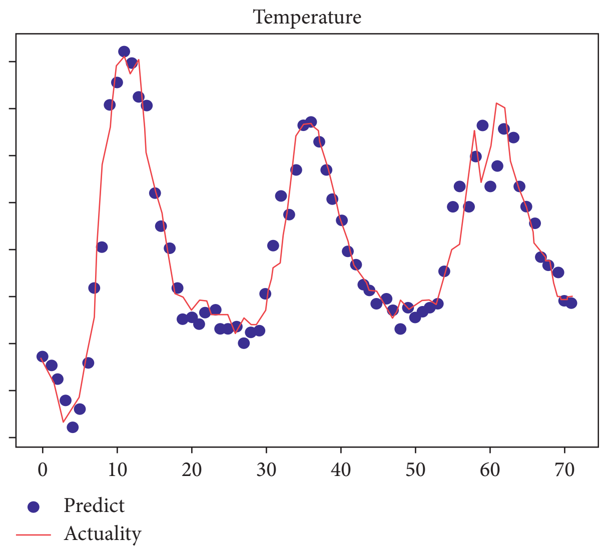


FIGURE 33: 24 h real-time temperature and predicted state diagram.

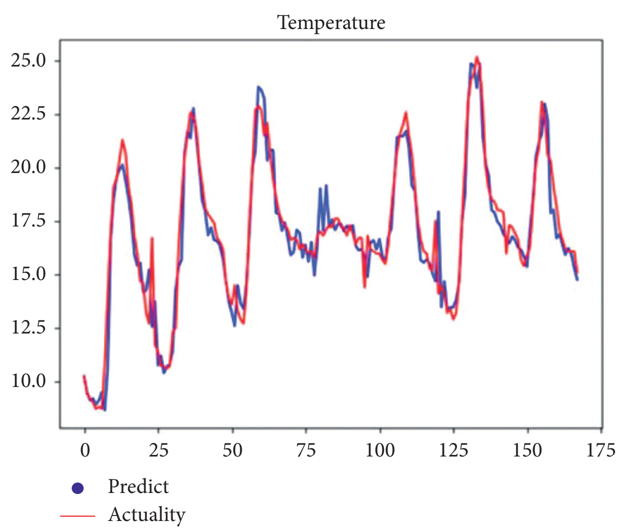


FIGURE 34: Real-time temperature and predicted state for a week.

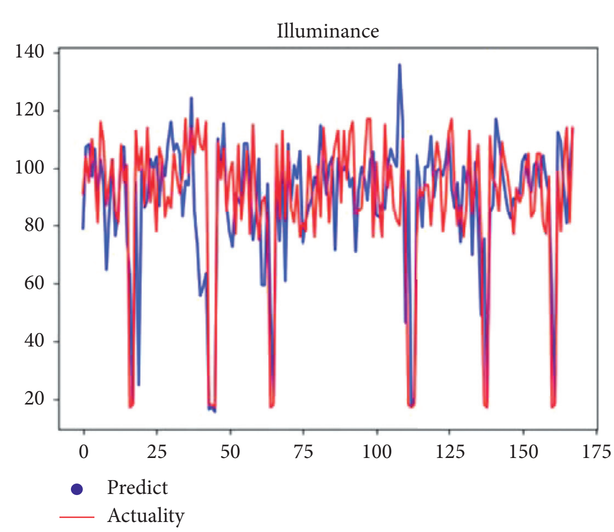


FIGURE 35: Real-time illuminance and forecast state diagram for a week.

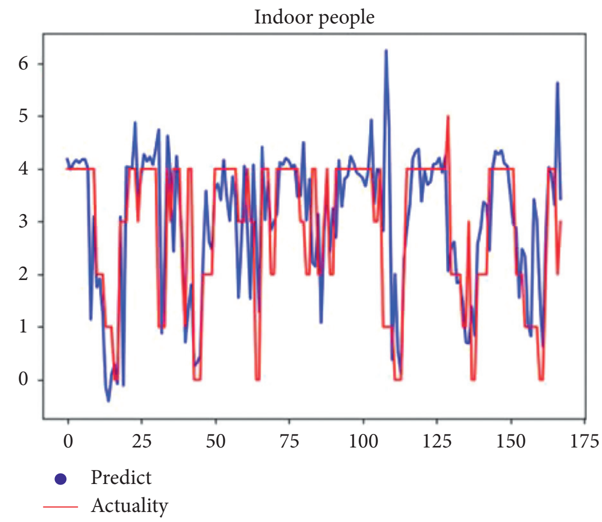


FIGURE 36: Real-time person count for a week and the forecast state diagram.

5. Conclusion

In this study, home environment sensing and prediction were successfully achieved to realize the smart control of a home environment. LabVIEW was utilized as the main interface of this smart home system. An ANN AI model constructed using Python was integrated into the LabVIEW system. This combination provided the advantages of both software systems, namely, the excellent monitoring and control interface of LabVIEW and the excellent AI algorithm calculation capabilities of Python. In this study, the sign-in protection function, smart home environment sensing and control, real-time data collection and prediction, and AI model and training were separated, as described in the study. Moreover, different AI models can be integrated into the system, such as the RNN and LSTM. Furthermore, the proposed system can be applied to many different systems to endow them with AI capabilities, such as robots and vehicles.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was funded by the Ministry of Science and Technology, Taiwan (MOST 109-2511-H-018 -018 -MY3).

References

[1] J. Jaihar, N. Lingayat, P. S. Vijaybhai, G. Venkatesh, and K. P. Upla, “Smart home automation using machine learning algorithms,” in *Proceedings of the 2020 International*

Conference for Emerging Technology (INCET), pp. 1–4, Belgaum, India, June 2020.

[2] H. Verma, M. Jain, K. Goel, A. Vikram, and G. Verma, "Smart home system based on Internet of Things," *International Journal of Advanced Computer Science and Applications (IJACSA)*, vol. 11, no. 2, pp. 2073–2075, 2020.

[3] A. Kazarian, V. Teslyuk, I. Tsmots, and M. Mashevska, "Units and structure of automated "smart" house control system using machine learning algorithms," in *Proceedings of the 2017 14th International Conference the Experience of Designing and Application of CAD Systems in Microelectronics (CADSM)*, pp. 364–366, Lviv, Ukraine, February 2017.

[4] L. Salhi, T. Silverston, T. Yamazaki, and T. Miyoshi, "Early detection system for gas leakage and fire in smart home using machine learning," in *Proceedings of the 2019 IEEE International Conference on Consumer Electronics (ICCE)*, pp. 1–6, Las Vegas, NV, USA, February 2019.

[5] S. Casaccia, L. Romeo, A. Calvaresi et al., "Measurement of users' well-being through domotic sensors and machine learning algorithms," *IEEE Sensors Journal*, vol. 20, no. 14, pp. 8029–8038, 2020.

[6] A. J. Majumder and J. A. Izaguirre, "A smart IoT security system for smart-home using motion detection and facial recognition," in *Proceedings of the 2020 IEEE 44th Annual Computers, Software, and Applications Conference (COMPSAC)*, pp. 1065–1071, Madrid, Spain, July 2020.

[7] Z. Zhang, T. He, M. Zhu, Q. Shi, and C. Lee, "Smart triboelectric socks for enabling Artificial Intelligence of Things (AIoT) based smart home and healthcare," in *Proceedings of the 2020 IEEE 33rd International Conference on Micro Electro Mechanical Systems (MEMS)*, pp. 80–83, Vancouver, BC, Canada, January 2020.

[8] D. Ganesh, G. Seshadri, S. Sokkanarayanan, S. Rajan, and M. Sathiyanarayanan, "IoT-based google duplex artificial intelligence solution for elderly care," in *Proceedings of the 2019 International Conference on Contemporary Computing and Informatics (IC3I)*, pp. 234–240, Singapore, December 2019.

[9] Y. Arora, H. Pant, and Banita, "Home automation system with the use of Internet of Things and artificial intelligence," in *Proceedings of the 2019 International Conference on Innovative Sustainable Computational Technologies (CISCT)*, pp. 1–4, Dehradun, Uttarakhand, India, October 2019.

[10] A. Kazarian and V. Teslyuk, "Optimization of neural network structure for smart house systems," in *Proceedings of the 2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON)*, pp. 562–565, Lviv, Ukraine, October 2019.

[11] S. Aggarwal and A. Kumar, "A smart irrigation system to automate irrigation process using IOT and artificial neural network," in *Proceedings of the 2019 2nd International Conference on Signal Processing and Communication (ICSPC)*, Coimbatore, India, March 2019.

[12] H. Zhao et al., "Learning-based occupancy behavior detection for smart buildings," in *Proceedings of the 2016 IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 954–957, Montreal, QC, August 2016.

[13] A. Legrand, B. Niepceron, A. Cournier, and H. Trannois, "Study of autoencoder neural networks for anomaly detection in connected buildings," in *Proceedings of the 2018 IEEE Global Conference on Internet of Things (GCIoT)*, pp. 1–5, Alexandria, Egypt, December 2018.

[14] A. Zaza, S. Al-Emadi, and S. Kharroub, "Modern QoS solutions in WSAN: an overview of energy aware routing protocols and applications," in *Proceedings of the 2020 IEEE International Conference on Informatics, IoT, and Enabling Technologies (ICIoT)*, pp. 581–589, Doha, Qatar, February 2020.

[15] R. A. Rashid, L. Chin, M. A. Sarijari, R. Sudirman, and T. Ide, "Machine learning for smart energy monitoring of home appliances using IoT," in *Proceedings of the 2019 Eleventh International Conference on Ubiquitous and Future Networks (ICUFN)*, pp. 66–71, Zagreb, Croatia, July 2019.

[16] N. Najari, S. Berlemont, G. Lefebvre, S. Duffner, and C. Garcia, "Network traffic modeling for IoT-device re-identification," in *Proceedings of the 2020 International Conference on Omni-Layer Intelligent Systems (COINS)*, pp. 1–6, Barcelona, Spain, July 2020.

[17] T. Matsui, K. Onishi, S. Misaki, M. Fujimoto, H. Suwa, and K. Yasumoto, "Easy-to-deploy living activity sensing system and data collection in general homes," in *Proceedings of the 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, pp. 1–6, Austin, TX, USA, March 2020.

[18] K.-C Yao, W.-T Huang, L.-C. Hsu, J.-Y. Lai, and C.-K. Yang, "ICIC express letters, part B: applications," *An International Journal of Research and Surveys*, vol. 7, no. 11, 2016.

[19] S. K. Bhoi, S. Kumar Panda, B. Narayan Padhi et al., "FireDS-IoT: a fire detection system for smart home based on IoT data analytics," in *Proceedings of the 2018 International Conference on Information Technology (ICIT)*, pp. 161–165, Bhubaneswar, India, December 2018.

[20] R. A. Nadaf, M. Rubina, P. Sujata, and V. M. Bonal, "Smart mirror using Raspberry Pi for human monitoring and intrusion detection," in *Proceedings of the 2019 1st International Conference on Advances in Information Technology (ICAIT)*, pp. 116–121, Chikmagalur, India, July 2019.

[21] K.-C. Yao, W.-T Huang, C.-Y. Lo, L.-C. Hsu, and J.-S. Chiang, "IoT application on remote monitoring and control of museum display cabinet," *ICIC Express Letters*, vol. 10, no. 9, pp. 2249–2257, 2016.

[22] R. S. Govindaraju, "Artificial neural networks in hydrology. I: preliminary concepts," *Journal of Hydrologic Engineering*, vol. 5, no. 2, pp. 115–123, 2000.

[23] K.-C. Yao, W.-T. Huang, and L.-C. Hsu, "Evaluation of the established IoT smart home robot teaching model based on embedded thematic-approach strategy," *Mathematical Problems in Engineering*, vol. 2020, Article ID 6696155, 10 pages, 2020.