

Research Article

Simulation Framework for Cyber-Physical Production System: Applying Concept of LVC Interoperation

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In Industry 4.0, many manufacturers have built smart factories by ICTs (Information and Communications Technology), and simulation is one of the core technologies for smart manufacturing. Various kinds of simulations, depending on system levels, such as assembly line, logistics, worker, and process, are utilized for smart manufacturing. Manufacturers own heterogeneous simulations; however, they have difficulty integrating and interoperating them. This paper proposes a novel simulation framework for smart manufacturing based on the concept of live, virtual, and constructive (LVC) simulation. The LVC interoperation provides a synthetic simulation environment with the above three types of simulations. With the LVC interoperation, we propose a systematic and efficient architecture for smart manufacturing. To be specific, the interface technologies between the heterogeneous simulations and their interoperable methods are developed. Finally, we provide a practical LVC simulation applied in the manufacturing company and show what synergy can be created using the LVC simulation.

1. Introduction

Smart manufacturing is a broad category of manufacturing which employs computer-integrated manufacturing, high levels of adaptability and rapid design changes, digital information technology, and more flexible technical workforce training [1, 2]. In the era of the fourth industrial revolution, as ICTs such as Internet of Things (IoT), big data, artificial intelligence, and Virtual Reality/Augmented Reality (VR/AR) develop, manufacturing systems are becoming more intelligent and unmanned [3, 4]. For example, through the IoT sensors, real-time data such as various facilities, workers, transportation equipment, and factory environment can be obtained [5, 6]. It enables real-time fault detection and diagnosis [7–9]. Also, the acquired big data can be used to analyze and predict shop floor through artificial intelligence and machine-learning techniques [10]. Also, users can apply VR/AR to a manufacturing system to plan and test a complex manufacturing process or assembly process in advance [11]. Logistics and equipment management

are possible through this virtual manufacturing environment. We can utilize these ICTs to increase production efficiency [12].

Many manufacturing companies introduce a cyber-physical production system (CPPS) to innovate production using ICTs [13–16]. With smart manufacturing, it is possible to make decisions and perform tasks before actual plant construction and to solve problems that can occur in mass production in a virtual environment in advance [17]. Also, even after plant construction, it can be used for maintenance, such as the optimal operation of production lines and fault diagnosis, to increase the production competitiveness [18]. As interest in smart manufacturing increases, the importance of simulation, a key technology for this, is also increasing [19]. In manufacturing, there are various kinds of simulations depending on system levels or purposes, such as assembly line simulation, logistics simulation, process simulation, and worker simulation. Manufacturers are using these approaches to build smart factories, but they are having difficulty integrating and interoperating these heterogeneous simulations [20].

Therefore, this paper proposes a new simulation framework for CPPS which applies the concept of live, virtual, and constructive (LVC) interoperation. The LVC interoperation is a widely applied concept in the defense modeling and simulation (M&S) domain [21]. It establishes a synthetic theater of war by integrating or interoperating three heterogeneous simulations: live, virtual, and constructive [22]. In production, individual simulation technologies have developed along with smart manufacturing. An operation plan for integrating them is needed, and the LVC in the defense domain, which has relatively developed interoperation architecture, can be applied and implemented [23].

In the manufacturing domain, there were many simulations at each layer, but there were few requirements for training/analysis through simulation interoperation like defense domain. But, the recent rise of smart factories has increased the need for convergence of existing simulations. However, research on individual case studies rather than the overall interoperation framework is still the main focus. Therefore, the concept of LVC interoperation can be applied to the smart manufacturing to build a systematic and efficient smart manufacturing architecture.

There have been some studies where simulations were utilized to build the smart factory and others that applied to the smart manufacturing by interoperating process simulator and line simulator [24, 25]. They yielded more accurate simulation results through the interoperation. However, interoperation was used for distributed execution of the same level of simulators rather than interoperation with different levels of simulators [26]. In addition, they show only individual interoperation cases and do not suggest an overall architecture throughout the smart factory.

There were also studies on the simulation direction of the CPPS-based factory [27]. They built a digital twin by implementing the corresponding physical components in the production process as digital components. However, since the system levels and characteristics of many components in the production process are different, it is difficult to implement and integrate them into one environment. Therefore, they are just suggesting an overall concept or implementing some parts of it. Thus, it is important to utilize the existing simulators at each level. To this end, the interoperation architecture of manufacturing simulation and the interface construction are required [28]. This paper not only creates synergy by interoperating existing simulators for smart manufacturing but also increases reusability and modularity. In addition, through this LVC interoperation for smart manufacturing, it presents the operational plan and future for the smart manufacturing.

The remainder of the paper is organized as follows. Section 2 presents the basic knowledge about LVC interoperation. Section 3 provides a novel LVC interoperation for CPPS-based smart manufacturing and discusses an application plan of the proposed work in the shop floor of the smart manufacturing. A case study of applying the proposed approach is described in Section 4. Finally, Section 5 concludes the discussion.

2. Concept of LVC Interoperation

The LVC interoperation technology integrates and operates three heterogeneous simulators as shown in Figure 1. It is a concept commonly used in the defense system and to build a field and efficient training system by interoperation of three resources [21].

The live simulation refers to training actual forces in the actual environment. The virtual simulation refers to training actual forces in the same virtual environment as the actual equipment. The constructive simulation means training by operating virtual forces under the virtual environment.

Live simulation can increase the reality because actual forces perform in the actual environment, but it takes a lot of time/resources and is limited to operating multiple times. Virtual simulations, such as aircraft simulators or tank simulators, can simulate equipment that is difficult to operate with a small cost and little time using a virtual environment, but there is a limit to understanding the overall training situation for various situations. Constructive simulation such as war games can simulate various scenarios, but it is relatively out of touch with reality and it is difficult to describe each object in detail [29].

Thus, these three simulations have different advantages and disadvantages, and they can be interoperated to build a synthetic theater of war. Through this, the distributed operations complement the advantages and disadvantages of each other and enable low-cost, high-efficiency training. Successful interoperation of LVC requires integrability of infrastructures, interoperability of systems, and composability of models [30].

At this time, LVC can communicate using interoperation middleware such as High Level Architecture/Run Time Infrastructure (HLA/RTI), as shown in Figure 1. The HLA/RTI is a middleware that implements an international standard for distributed simulation defined in IEEE 1516. It allows real-time data exchange and time management between heterogeneous simulators [31–33]. These interoperation technologies play important roles in constructing the LVC system. In particular, the establishment of interoperation standards increases the reusability and operability of the simulators.

Meanwhile, in the production domain, various simulators have been developed along with the smart manufacturing, and some ideas are needed to integrate them. In this paper, we use the relatively more developed concept of LVC interoperation in the defense domain to implement a novel interoperation architecture in the production domain. In the next section, we apply the concept to build a systematic and efficient interoperation architecture for smart manufacturing.

3. Applying LVC Interoperation into Smart Manufacturing

In this section, we propose an LVC interoperation for CPPS-based smart manufacturing. Firstly, we explain each component of LVC. Then, we provide the overall interoperation architecture and application plan in the shop floor of smart manufacturing.

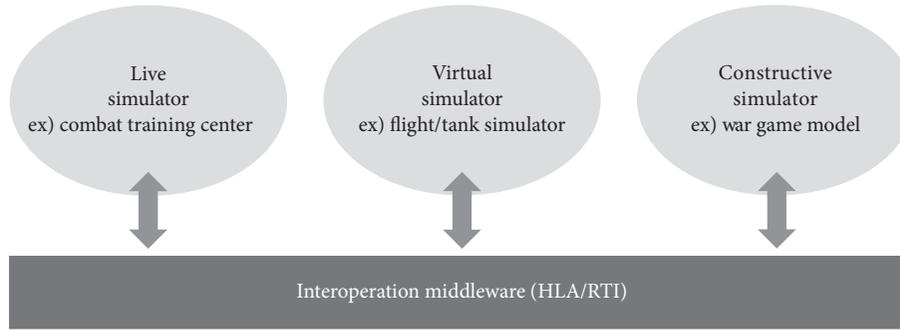


FIGURE 1: Concept of LVC interoperation.

3.1. Components of LVC in Smart Manufacturing. This section describes how to define and operate each component of LVC simulation in smart manufacturing. First, the concept of live simulation is shown in Figure 2. Live simulation in the smart manufacturing can be performed by actual workers on the assembly line or logistics on the actual shop floor. For example, workers can install IoT sensors and cameras when performing the assembly or logistics work and acquire real-time data through the attached sensors and cameras. The data obtained through the live simulation can be used to improve work proficiency and inefficient operation/behavior.

Figure 3 shows the actual live simulation that we are currently operating. When a real worker with IoT sensors performs assembly work, we can monitor operations through the sensors and the camera. The collected data allows us to measure the cycle time of the work, analyze the motion that is being wasted, and give feedback to the worker.

Next, the concept of virtual simulation is shown in Figure 4. Virtual simulation is a kind of hardware-in-the-loop (HIL) simulation in which users operate virtual simulators through hardware such as a Human Interface Device (HID). For example, a user can perform a simulation of an operation through a controller connected to a process simulator such as a machine or robot. At this time, the real-time results of the simulator return to the user in real time, and the user can perform the closed-loop simulation by constantly reflecting the feedback.

In addition, the user can experience and review the 3D Visual Factory using the VR/AR devices. As technologies such as VR/AR are developed and cooperated with existing virtual simulators, the spectrum of virtual simulation is expanding. Figure 5 is an example of a 3D virtual factory currently operating in the manufacturing facilities. The 3D virtual simulation model is implemented identically with the actual factory layout. It receives real-time data from the actual manufacturing line through the sensors. If abnormal data is detected, an alarm appears on the model and the user can detect it using equipment such as a VR Glass. This facilitates monitoring the manufacturing line and remote support. Another possible application using a VR device is an assembly test in the virtual work place. Usually implemented to validate workability of new work such as collision, reachability, or productivity, we need to build a new workshop for pilot testing. However, using VR/AR

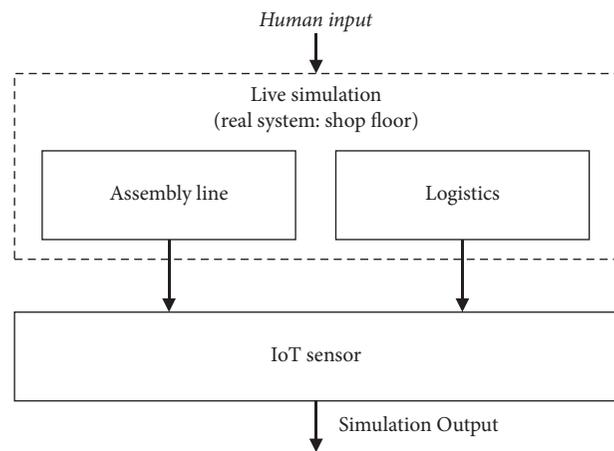


FIGURE 2: Concept of live simulation in smart manufacturing.

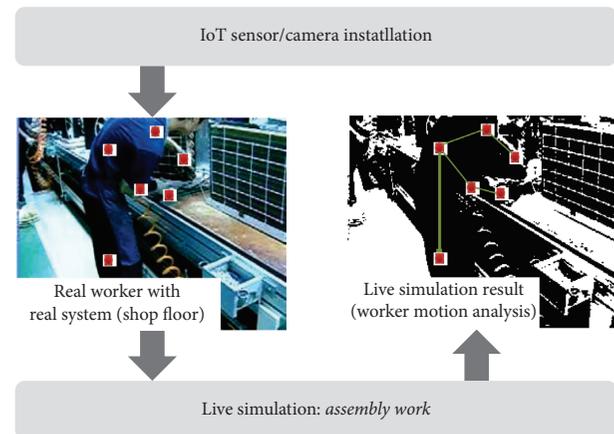


FIGURE 3: Application of live simulation in smart manufacturing.

technology, the worker can perform tasks in a virtual world without real workshop or tools.

Finally, the concept of constructive simulation is shown in Figure 6. Constructive simulator consists of constructive simulation model and constructive simulation engine. The simulation model used in this paper consists of three levels of models: the parameter-based model, the icon-based model, and the source code model so that all users in the production system can use the simulator [34]. The users can build a model in three ways

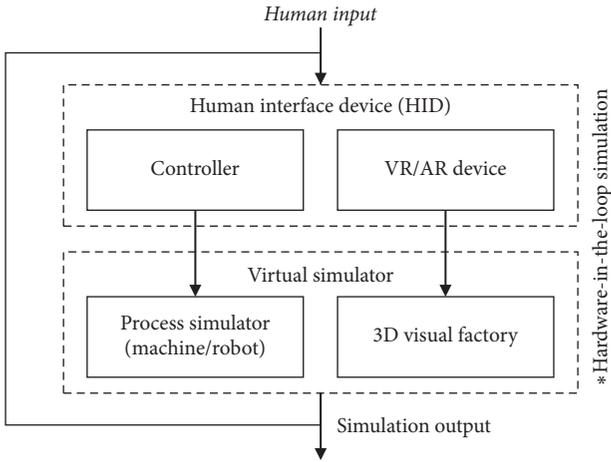


FIGURE 4: Concept of virtual simulation in smart manufacturing.

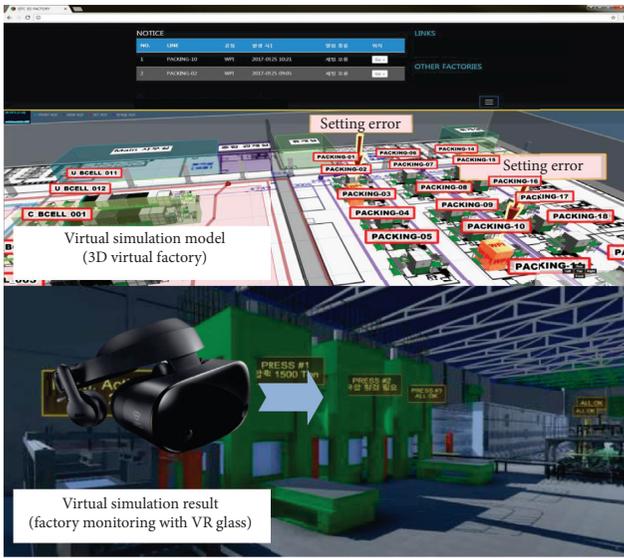


FIGURE 5: Application of virtual simulation in smart manufacturing.

depending on their simulation training level or simulation objective. The model is automatically created through the Production Line Generator and the Model Synthesizer inside the simulation engine as shown in Figure 6. Created as a discrete event simulation model, it can be simulated using a discrete event simulation engine. Although the fidelity is relatively low, the constructive simulation has the advantage of simulating production facilities quickly and repeatedly with virtual agents in a virtual environment.

An example of the constructive simulator that we are currently operating is shown in Figure 7. The upper part of Figure 7 shows the user modeling results of the assembly line and logistics through the icon-based modeling. The lower part of Figure 7 shows the simulation results using the automatically generated model from the user modeling result. Table 1 shows the results of comparing the features of three simulations in smart manufacturing.

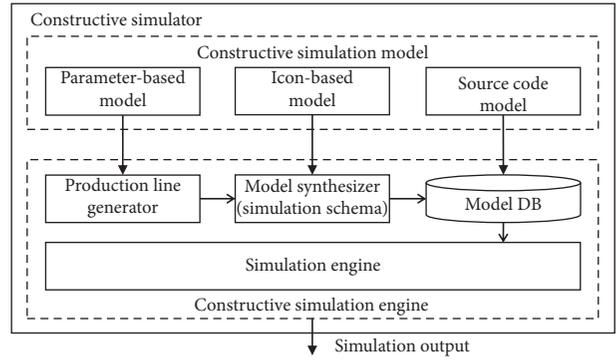


FIGURE 6: Concept of constructive simulation in smart manufacturing.

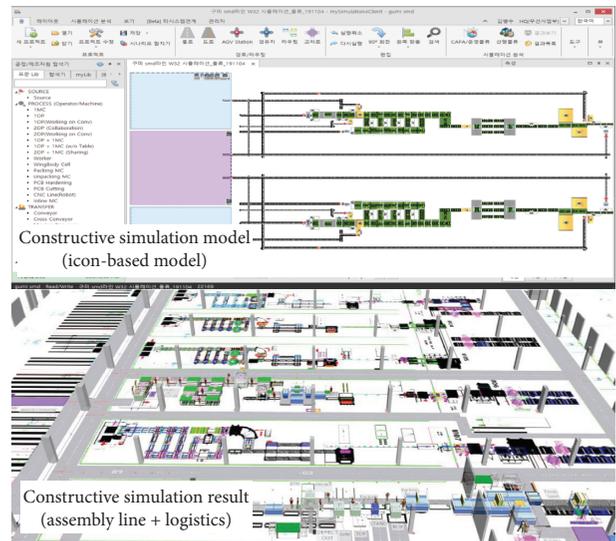


FIGURE 7: Application of constructive simulation in smart manufacturing.

3.2. Overall Architecture and Application Plan. Since modeling is objective-oriented, it is possible to model in various ways according to the objective of analysis in the manufacturing system. Although each simulation described in the previous section can be operated individually according to its purpose, it is important to create synergy by integrating them to build a more efficient smart manufacturing system. Figure 8 shows the overall architecture for LVC interoperation in smart manufacturing. Three simulations communicate using an interoperation interface, and the events they exchange are defined as shown in the figure. The interface consists of a proxy for message communication, a neutral data format, and a management tool for managing data/time. The following subsections describe the application plan for each LC, VC, and LV inside the overall interoperation architecture in detail.

First, LC interoperation will be described. The live simulation senses the operation of the worker through the IoT sensor and transmits the results to the constructive

TABLE 1: Characteristics of live, virtual, and constructive.

Characteristic	Live	Virtual	Constructive
Unit	Real	Real	Virtual
Environment	Real	Virtual	Virtual
Type	Real work	Process simulator, 3D virtual factory	Manufacturing facilities
Tool	IoT sensors, camera	HID, VR/AR device	Personal computer
Objective	Training, real data acquisition	Training	Analysis
Pros and cons	Realistic simulation, but requires a lot of cost and time	Actual environment is unnecessary	Rapid analysis time and less cost, but high abstraction level

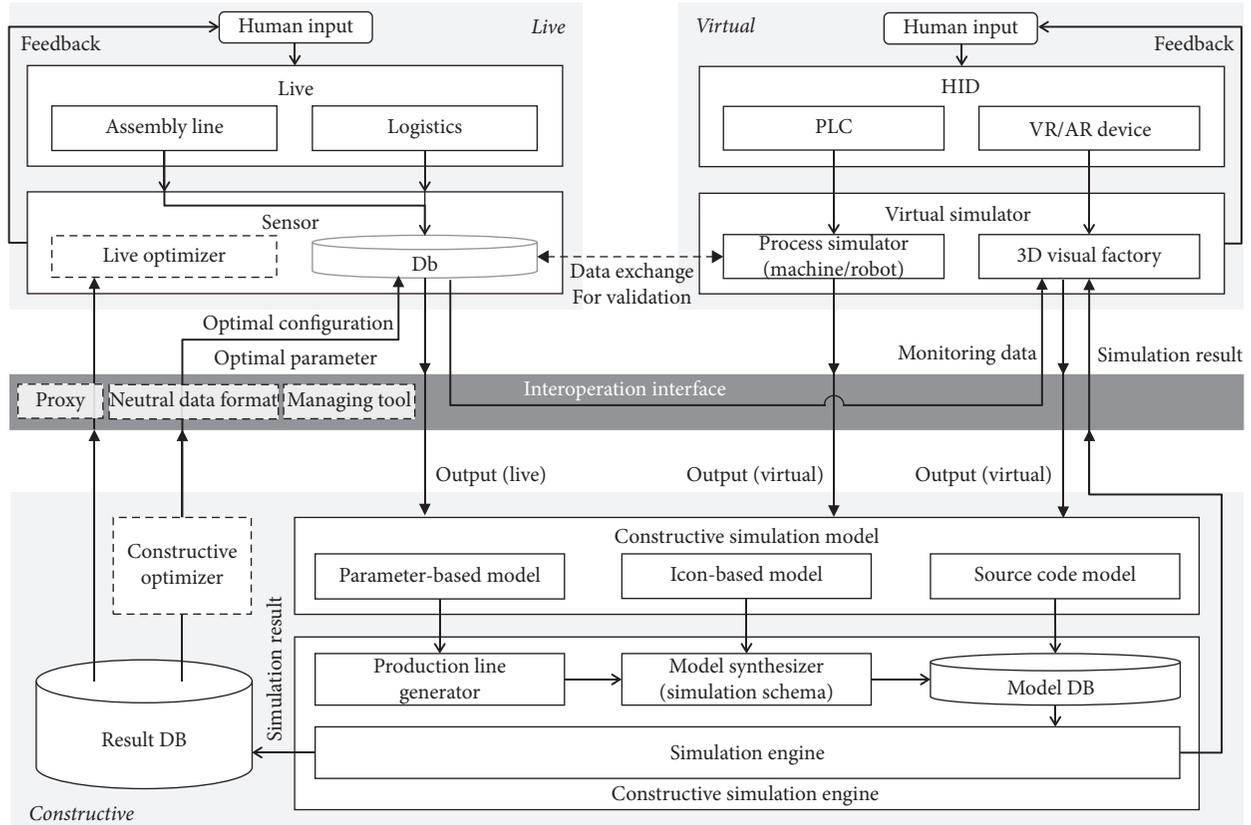


FIGURE 8: Overall architecture of LVC interoperation in smart manufacturing.

simulator in real time. The constructive simulator takes them and performs layout simulation to predict the productivity. The optimal line configurations or parameters derived from simulation-based optimization (constructive optimizer) return to the worker or shop floor to help improve the productivity. For example, by deriving the optimal cycle time for the desired throughput or line of balance (LOB), it can provide the improvement points of the operator's waste operation and the facility's performance. It can also provide a way to improve the shop floor such as with assembly line layout and logistics traffic. In other words, we can derive efficient manufacturing conditions by simulation-based optimization using interoperation of sensing data and simulation models [35, 36]. Also, we can optimize the results of the constructive simulation through the motion analysis (live optimizer) in the live simulation. Details of this procedure will be covered in the case study.

Next, one of VC interoperations is an operation with layout simulator and process simulator using HID. By replacing part of the virtual layout model with the process simulator, it is possible to do virtual commissioning that the user controls through the controller in real time. Virtual commissioning can dramatically reduce system installation costs and operating time by simulating and verifying automation equipment in a virtual environment to ensure that the equipment works as expected [37, 38]. The layout simulator can be interoperated with the virtual simulator as well as the actual machine. This enables the feasibility and interoperability test between equipment and assembly line and allows more detailed simulation of the manufacturing system through the interoperation between different levels of simulators. In addition, there is an interoperation between VR/AR device and layout simulator as another method of VC interoperation. Using the layout modeling environment,

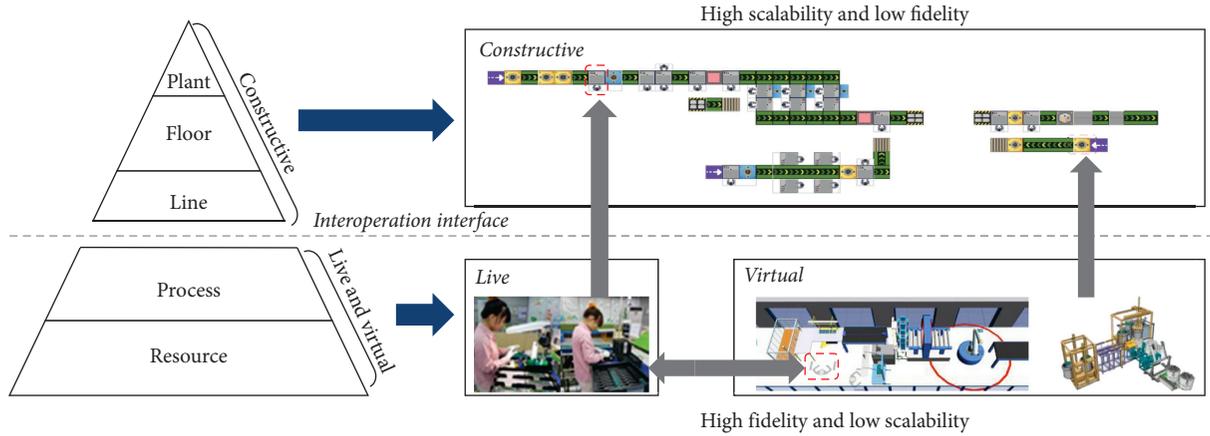


FIGURE 9: LVC interoperation example.

we can model the manufacturing plant as a 3D virtual factory and experience it using VR/AR devices. In addition, intuitive fault detection and diagnosis is possible by transmitting the real-time prediction results of the layout simulation to the virtual environment. It enables monitoring the manufacturing line with a remote support.

Next, one of LV interoperations is an analysis of virtual facilities in conjunction with actual facilities. In other words, a virtual simulator can be validated through comparison of data between virtual and actual facilities. The parameters applied to the virtual simulator can be tuned through the results of the actual equipment, and synergy can be created by performing high-scalable simulation using these validated simulators. In addition, it is possible to monitor the operating status through the 3D virtual factory by sharing the actual operation status and results of the live simulation. On the other hand, it is possible to test and validate new workshop or improved tasks in a virtual environment. Newly designed workshop can be constructed as a virtual simulation model, and a worker can perform tasks using VR without the actual workshop. At the same time, IoT sensors attached to the worker collect motion data and transmit the data to analysis.

Finally, we can operate smart manufacturing by interoperation of all three LVC simulations. Figure 9 shows a simple example of LVC interoperation. The LVC interoperation concept was applied to the hybrid simulation for advanced analysis of the manufacturing system. Among the five components that make up the factory, high-level components such as plant, floor, and line can be expressed using constructive simulation. They have high scalability but low fidelity. On the other hand, low-level components such as process and resource can be expressed by live simulation and virtual simulation depending on the type. They have low scalability but high fidelity on the contrary. By interoperating the simulations at different levels, it is possible to predict the manufacturing system more precisely. In the case study, we will show a simple example of LVC interoperation using these operation plans.

Likewise, with the LVC interoperation framework for smart manufacturing, various application plans can be

operated depending on the needs of the shop floor as described above. Through the framework, three heterogeneous simulators can achieve organic cooperation and increase interoperability/connectivity. As a result, the gap between the real and cyber world can be bridged, and CPPS-based smart manufacturing system can be finally established. In the case study, we will show a simple example of LVC interoperation using these operation plans.

4. Case Study

Generally, manufacturers use simulations to build new production lines or improve existing production lines. The simulation predicts the production of the lines in advance and finds ways to optimize the line. At this time, the process time per resource, which is the input data of the simulation model, actually utilizes the data measured in the line. This section describes a case where LVC interoperation was performed by applying this.

Figure 10 shows the layout of the linear production line used for the case study. It is one of simple test lines in our company. Five workers and one automation machine perform six separate processes from the left, and a conveyor is placed between each process to move the finished product from the previous process to the next. The user creates a model of constructive simulation based on the layout and performs the simulation. At this time, the process time per resource is obtained from live simulation and used. Table 2 is the time of the process and the process for each resource used in the case study. Here, the process time is obtained differently depending on the resource type. The worker's value is measured by attaching an IoT sensor. In the case of the machine, it is obtained by analyzing the log data about the operation of the machine through OPC UA.

Figure 11 shows the results of constructive simulation modeling by placing a library that represents the process of resources in the production line and Figure 12 shows the actual process (working, blocking, and waiting) load results for each process when the simulation is performed for 460 minutes. The legend is expressed on the right side of the graph. Through this, it can be confirmed that the assembly



FIGURE 10: Layout for production line used in case study.

TABLE 2: Process time and resource by process in the production line of the case study.

No.	Process	Process time			Resource
		Min	Avg.	Max	
1	Input	8.81	15.66	20.81	Worker
2	Preassembly	9.60	15.57	21.71	Worker
3	Assembly cell 1	16.61	18.61	21.6	Worker
4	Assembly cell 2	14.53	18.60	22.51	Worker
5	Inspection	13.95	18.00	19.50	Machine
6	Packing	13.39	16.40	20.42	Worker

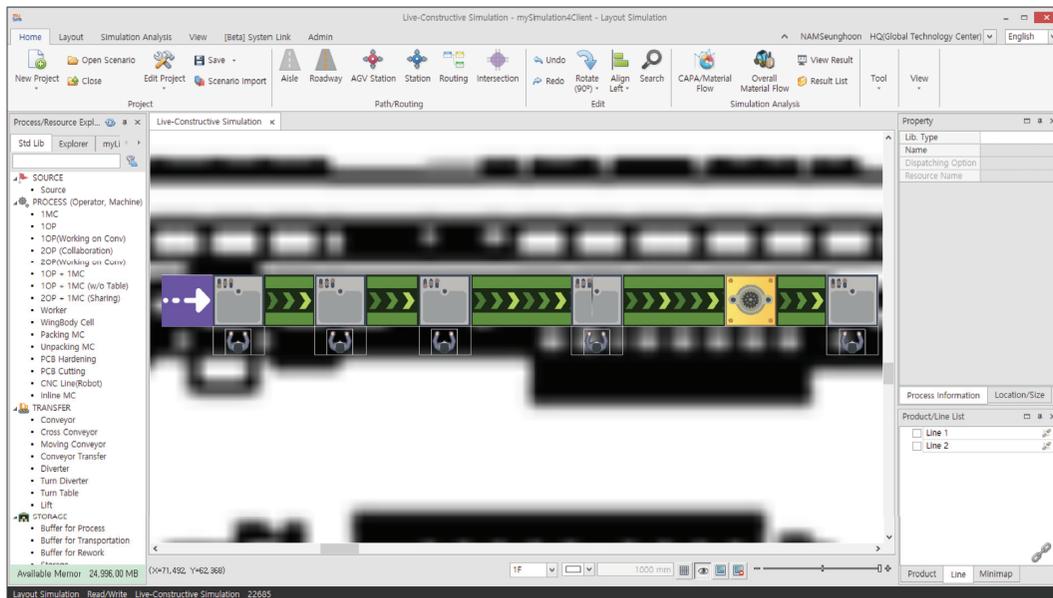


FIGURE 11: Constructive simulation modeling results for the linear production line.

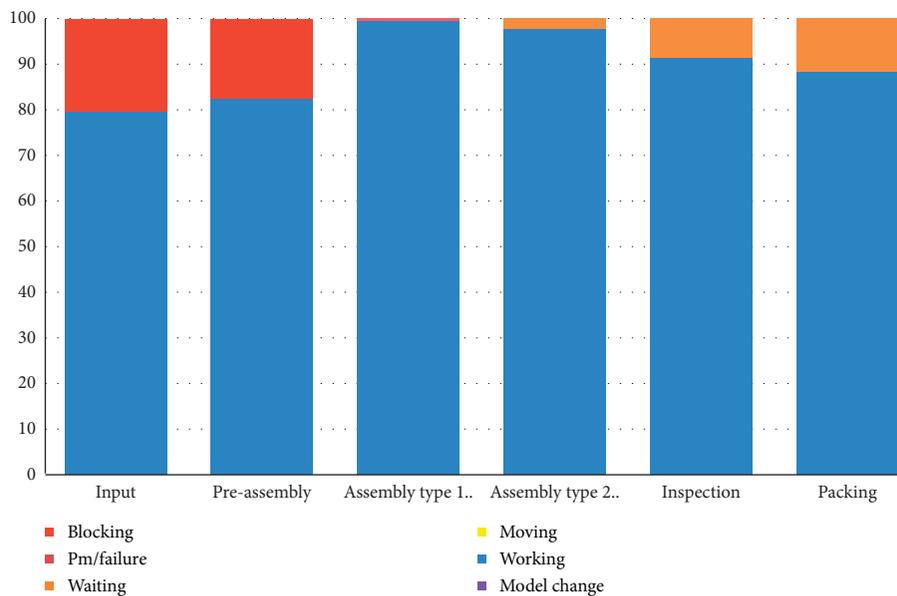


FIGURE 12: Simulation results of process load for initial measured process time.

TABLE 3: Throughput, cycle time, and working time for each process in the line.

No.	Process	Throughput	Cycle time	Working time
1	Input	1,460	18.9	15.02
2	Preassembly	1,459	18.92	15.61
3	Assembly cell 1	1,457	18.94	18.9
4	Assembly cell 2	1,455	18.97	18.49
5	Inspection	1,454	18.98	17.36
6	Packing	1,453	19	16.78

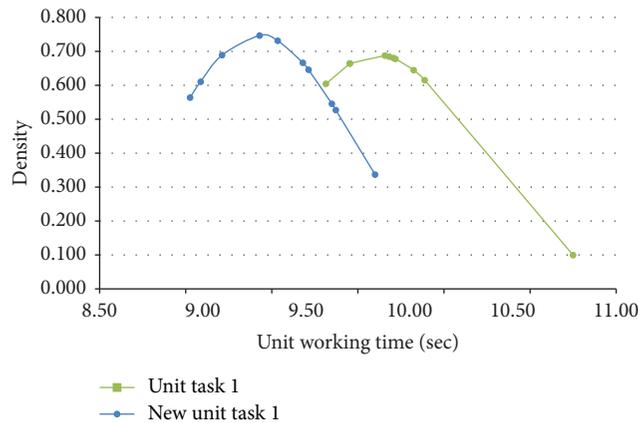


FIGURE 13: Working time distribution curve for unit task 1 of the assembly cell.

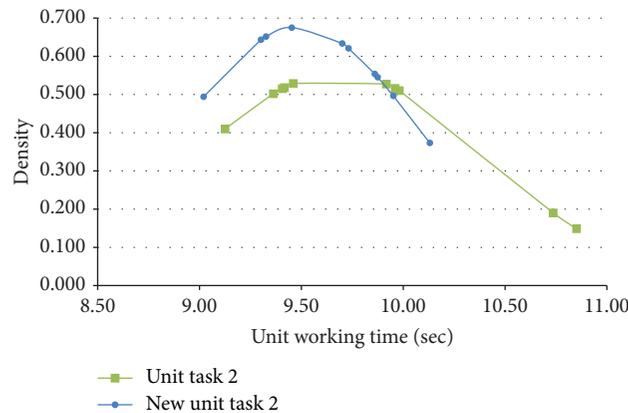


FIGURE 14: Working time distribution curve for unit task 2 of the assembly cell.

type 1 process that generates a blocking in the previous process and generates a waiting in the next process is a bottleneck process. The throughput of each process, cycle time, and working time are shown in Table 3. The total production of the line is 1,453, which is the throughput of the last process.

To optimize the line based on the results, this study restructured the process time for assembly cell 1, which was analyzed as a bottleneck through the results of constructive simulation. Assembly cell 1 consists of two unit tasks. By performing motion analysis within each unit task, unnecessary operations are removed and the locations of tool and

parts are relocated. To forecast the new process time of improved task in the suggested new workshop layout, the virtual workshop was constructed in detail so that a worker performed the new task in a virtual environment using VR device.

As a result, process time of assembly cell 1 is shortened by improving work behavior and new workshop layout. The sample data (Figures 13 and 14) show the normal distribution curve for the existing unit working time and the changed unit working time. Constructive simulation was performed again to reflect this result. The lead time of all lines was reduced and the production was increased

TABLE 4: Throughput, cycle time, and working time per process in the line according to work time reorganization.

No.	Process	Throughput	Cycle time	Working time
1	Input	1,493	18.49	15.07
2	Preassembly	1,491	18.51	15.54
3	Assembly cell 1	1,489	18.54	18.17
4	Assembly cell 2	1,487	18.56	18.5
5	Inspection	1,485	18.59	17.42
6	Packing	1,484	18.6	16.72

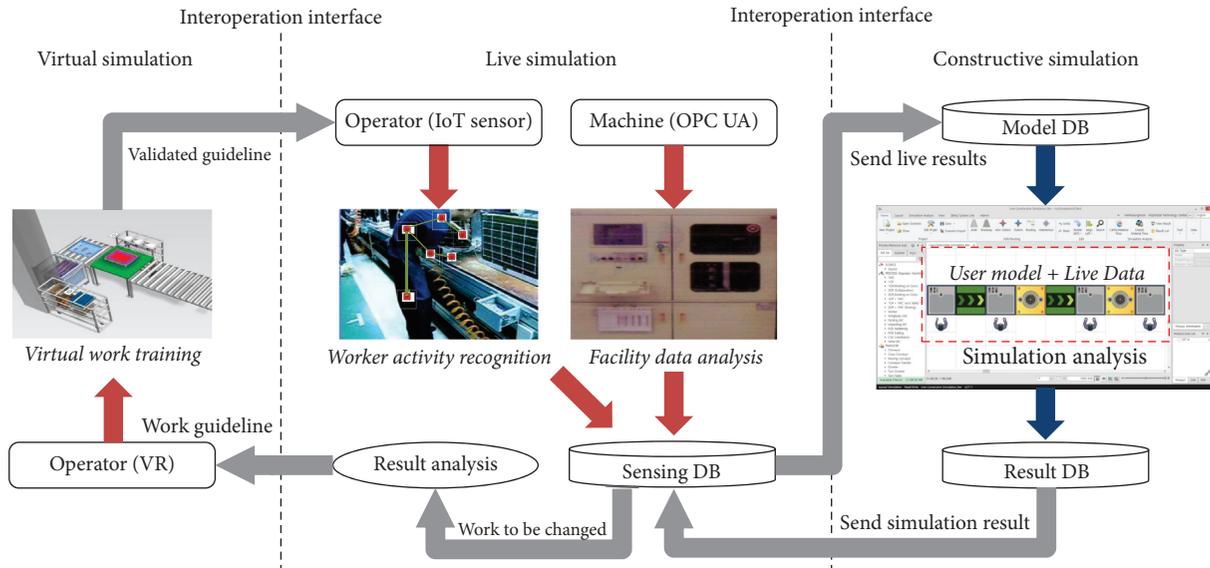


FIGURE 15: The LVC interoperation procedure performed in the case study.

(Table 4). The procedure performed in this case study is represented by a diagram as shown in Figure 15. This case study has shown that organic interoperation of three heterogeneous simulations can contribute to improve productivity and create synergy.

5. Conclusion

In the fourth industrial revolution, many manufacturing enterprises are building smart manufacturing platforms using various ICTs. As interest in smart manufacturing increases, various simulators are being developed to simulate production sites according to the objective of analysis. Manufacturers continue to utilize these various simulators to build smart manufacturing systems. However, they have difficulty integrating and interoperating existing heterogeneous simulators for smart manufacturing. In other words, we need a whole framework for interoperating them. Therefore, this paper proposed an interoperation framework of manufacturing simulations by applying the existing LVC interoperation concept operated in the military domain. This framework provides an interoperation interface and interoperable methods between each simulation. Finally, we showed how we can utilize it through the actual case study of interoperation between live and constructive simulation. It presented a method to link the constructive simulation for one production line and the live simulation of

resources in the line. It was verified by performing one example of increasing production throughput of the production line through actual data. In addition, it has been able to improve the reusability and interoperability of existing simulations.

By using LVC, the feasible integration is started from the manufacturing stage, and the comprehensive smart factory including other legacy systems, such as Manufacturing Execution System and Supply Chain Management, can be built gradually. Finally, we will build and expand a Manufacturing Lifecycle Management system that covers everything from development to manufacturing. In addition, it is required to propose the direction of the smart factory through the LVC interoperation.

Data Availability

Data in this work are not freely available due to patient privacy and commercial confidentiality.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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References

- [1] F. Tao and M. Zhang, "Digital twin shop-floor: a new shop-floor paradigm towards smart manufacturing," *IEEE Access*, vol. 5, pp. 20418–20427, 2017.
- [2] X. Yao, J. Zhou, Y. Lin, Y. Li, H. Yu, and Y. Liu, "Smart manufacturing based on cyber-physical systems and beyond," *Journal of Intelligent Manufacturing*, vol. 30, no. 8, pp. 2805–2817, 2019.
- [3] J. Wan, M. Yi, D. Li, C. Zhang, S. Wang, and K. Zhou, "Mobile services for customization manufacturing systems: an example of industry 4.0," *IEEE Access*, vol. 4, pp. 8977–8986, 2016.
- [4] U. H. Govindarajan, A. J. C. Trappey, and C. V. Trappey, "Immersive technology for human-centric cyberphysical systems in complex manufacturing processes: a comprehensive overview of the global patent profile using collective intelligence," *Complexity*, vol. 2018, Article ID 4283634, 17 pages, 2018.
- [5] Y. Tan, W. Yang, K. Yoshida, and S. Takakuwa, "Application of IoT-aided simulation to manufacturing systems in cyber-physical system," *Machines*, vol. 7, no. 1, p. 2, 2019.
- [6] G. Hwang, J. Lee, J. Park, and T.-W. Chang, "Developing performance measurement system for Internet of Things and smart factory environment," *International Journal of Production Research*, vol. 55, no. 9, pp. 2590–2602, 2017.
- [7] K.-M. Seo and K.-P. Park, "Interface data modeling to detect and diagnose intersystem faults for designing and integrating system of systems," *Complexity*, vol. 2018, Article ID 7081501, 21 pages, 2018.
- [8] K. Y. H. Lim, P. Zheng, and C. H. Chen, "A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives," *Journal of Intelligent Manufacturing*, vol. 31, pp. 1313–1337, 2020.
- [9] A. J. H. Redelinghuys, A. H. Basson, and K. Kruger, "A six-layer architecture for the digital twin: a manufacturing case study implementation," *Journal of Intelligent Manufacturing*, vol. 31, no. 6, pp. 1383–1402, 2019.
- [10] B. S. Kim and T. G. Kim, "Modeling and simulation using artificial neural network-embedded cellular automata," *IEEE Access*, vol. 8, no. 1, pp. 24056–24061, 2020.
- [11] G. Chen, P. Wang, B. Feng, Y. Li, and D. Liu, "The framework design of smart factory in discrete manufacturing industry based on cyber-physical system," *International Journal of Computer Integrated Manufacturing*, vol. 33, no. 1, pp. 79–101, 2019.
- [12] S. Choi, C. Jun, W. B. Zhao, and S. Do Noh, "Digital manufacturing in smart manufacturing systems: contribution, barriers, and future directions," in *proceedings of the IFIP International Conference on Advances in Production Management Systems*, pp. 21–29, Tokyo, Japan, September 2015.
- [13] Q. Qi and F. Tao, "Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison," *IEEE Access*, vol. 6, pp. 3585–3593, 2018.
- [14] H. Tang, D. Li, S. Wang, and Z. Dong, "CASOA: an architecture for agent-based manufacturing system in the context of Industry 4.0," *IEEE Access*, vol. 6, pp. 12746–12754, 2017.
- [15] L. Ribeiro and M. Hochwallner, "On the design complexity of cyberphysical production systems," *Complexity*, vol. 2018, Article ID 4632195, 13 pages, 2018.
- [16] R. Lovas, A. Farkas, A. C. Marosi et al., "Orchestrated platform for cyber-physical systems," *Complexity*, vol. 2018, Article ID 8281079, 16 pages, 2018.
- [17] R. Rosen, G. Von Wichert, G. Lo, and K. D. Bettenhausen, "About the importance of autonomy and digital twins for the future of manufacturing," *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 567–572, 2015.
- [18] G. Y. Kim, J. Y. Lee, H. S. Kang, and S. D. Noh, "Digital factory wizard: an integrated system for concurrent digital engineering in product lifecycle management," *International Journal of Computer Integrated Manufacturing*, vol. 23, no. 11, pp. 1028–1045, 2010.
- [19] J. Jeon, S. Kang, and I. Chun, "CPS-based model-driven approach to smart manufacturing systems," *The Fifth International Conference on Intelligent Systems and Applications*, vol. 68, pp. 136–146, 2016.
- [20] R. Jardim-Goncalves, A. Grilo, and K. Popplewell, "Novel strategies for global manufacturing systems interoperability," *Journal of Intelligent Manufacturing*, vol. 27, no. 1, pp. 1–9, 2016.
- [21] DoD, *DoD Modeling and Simulation (M&S) Glossary. DoD 5000.59-M*, CreateSpace Independent Publishing Platform, Sacramento, CA, USA, 2013.
- [22] W. Choi, K. Yu, B. J. Park, S. Kang, and J. Lee, "Study on LVC (Live-Virtual-Constructive) interoperation for the national defense M&S (modeling & simulation)," in *Proceedings of the 2008 International Conference on Information Science and Security (ICISS 2008)*, pp. 128–133, Hyderabad, India, December 2008.
- [23] K.-M. Seo, W. Hong, and T. G. Kim, "Enhancing model composability and reusability for entity-level combat simulation: a conceptual modeling approach," *Simulation*, vol. 93, no. 10, pp. 825–840, 2017.
- [24] R. Bloomfield, E. Mazhari, J. Hawkins, and Y.-J. Son, "Interoperability of manufacturing applications using the Core Manufacturing Simulation Data (CMSD) standard information model," *Computers & Industrial Engineering*, vol. 62, no. 4, pp. 1065–1079, 2012.
- [25] B. P. Gan, L. P. Chan, and S. J. Turner, "Interoperating simulations of automatic material handling systems and manufacturing processes," in *Proceedings of the 2006 Winter Simulation Conference*, pp. 1129–1135, Sacramento, CA, USA, January 2006.
- [26] G. Pedrielli, M. Sacco, W. Terkaj, and T. Tolio, "An HLA-based distributed simulation for networked manufacturing systems analysis," *Journal of Simulation*, vol. 6, no. 4, pp. 237–252, 2012.
- [27] S. Weyer, T. Meyer, M. Ohmer, D. Gorecky, and D. Zühlke, "Future modeling and simulation of CPS-based factories: an example from the automotive industry," *IFAC-PapersOnLine*, vol. 49, no. 31, pp. 97–102, 2016.
- [28] J. Y. Lee, H. S. Kang, S. D. Noh, J. H. Woo, and P. Lee, "NESIS: a neutral schema for a web-based simulation model exchange service across heterogeneous simulation software," *International Journal of Computer Integrated Manufacturing*, vol. 24, no. 10, pp. 948–969, 2011.
- [29] M. Varshney, K. Pickett, and R. Bagrodia, "A live-virtual-constructive (LVC) framework for cyber operations test, evaluation and training," in *proceeding of the 2011 Military Communications Conference*, pp. 1387–1392, Baltimore, MA, USA, November 2011.
- [30] A. Tolk, "Interoperability and Composability," *Modeling and Simulation Fundamentals: Theoretical Underpinnings and Practical Domains*, pp. 403–433, John Wiley & Sons, Hoboken, NJ, USA, 2010.

- [31] IEEE Std 1516-2000, *IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA)-Framework and Rules*, IEEE Standard, Piscataway, NJ, USA, 2000.
- [32] IEEE Std 1516.1-2000, *IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA)-Federate Interface Specification*, IEEE Standard, Piscataway, NJ, USA, 2001.
- [33] IEEE Std 1516.2-2000, *IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA)-Object Model Template (OMT) Specification*, IEEE Standard, Piscataway, NJ, USA, 2001.
- [34] B. S. Kim, Y. Jin, and S. Nam, "An integrative user-Level customized modeling and simulation environment for smart manufacturing," *IEEE Access*, vol. 7, pp. 186637–186645, 2019.
- [35] B. S. Kim, B. G. Kang, S. H. Choi, and T. G. Kim, "Data modeling versus simulation modeling in the big data era: case study of a greenhouse control system," *Simulation*, vol. 93, no. 7, pp. 579–594, 2017.
- [36] B. S. Kim and T. G. Kim, "Cooperation of simulation and data model for performance analysis of complex systems," *International Journal of Simulation Modelling*, vol. 18, no. 4, pp. 608–619, 2019.
- [37] G. Reinhart and G. Wünsch, "Economic application of virtual commissioning to mechatronic production systems," *Production Engineering*, vol. 1, no. 4, pp. 371–379, 2007.
- [38] C. G. Lee and S. C. Park, "Survey on the virtual commissioning of manufacturing systems," *Journal of Computational Design and Engineering*, vol. 1, no. 3, pp. 213–222, 2014.