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Research Article

A Biobjective Model for Manual Materials Handling with Energy Consumption Being Accounted For

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Aiming at production environment and operation design in manual materials handling which often overlook workers' physiological factors and cause fatigue, even work-related musculoskeletal disorders, we construct a biobjective model based on economics and ergonomics. In the model, two objectives include functions about handling time and energy consumption. Based on the openness of IGRIP/ERGO simulation software combined with MATLAB, we design and develop the interactive simulation platform, where program language can be automatically generated. Then, we analyze the case about handling operations in an automobile brake pad manufacturing company, and the number of input materials and process scheduling are taken as research objects. Finally, the results show that the win-win optimal solution can be usually obtained between productivity and ergonomics for decision makers according to the proposed biobjective model. Moreover, the case study demonstrates that the interactive simulation platform can be devoted to providing the solution for modern production operation directly and conveniently, which can make the production environment and operation design in accordance with ergonomics.

1. Introduction

In the modern industrial systems, it is an important operation mode that employees assist in the production of automation equipment with the development of industrial automation. In order to develop in a competitive market, manufacturing enterprises usually ask professional process engineers to make standard time and constantly optimize based on time analysis in the traditional approaches [1, 2]. Profits can be gained by standardized production to improve production efficiency for enterprises, while workers must continue working in designated work locations and standard time by engineers. In the actual production, a large number of upper limb tasks are performed by workers, which include some typical actions like grasping, lifting, lowering, carrying, pushing, pulling, and walking in the workshop, especially manual materials handling (MMH) [3–6]. MMH tasks are common in various industries such as manufacturing, agriculture, hospital, and construction. Obviously, profit is the core for enterprises, so workers' capacities and productivity state are often overestimated [7–13]. Fredericks et al. pointed out that MMH is one of the major causes of severe industrial injury [12]. As for the construction industry, MMH tasks are very common on construction sites and are one of the major contributors for musculoskeletal disorders for workers by Li et al. [6]. Calzavara et al. indicated that it is recognized that MMH in warehouses exposes workers to a high risk of developing musculoskeletal disorders [13].

However, when employees maintain unhealthy state for a long time, cumulative metabolic waste will cause pain, and excessive and repetitive operation will lead to workers fatigue and develop into a pathological state. Unhealthy working environment and manual operations can result in work-related musculoskeletal disorders (WMSDs), which is the most common job-related occupational injury. WMSDs are injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and spinal discs such as lower back pain, neck-shoulder-wrist syndrome, and sprain [4, 11–15]. WMSDs are the leading cause of nonfatal occupational injuries that may lead to temporary or permanent disability. This urgent issue about WMSDs has become conspicuous day by day. For example, 25% of workers suffered from backache and 23% about muscular pains in Europe [16]. WMSDs accounted for 34% of all injury and illness cases in 2012, where MMH had the highest number in the USA [17]. WMSDs also showed high incidence, and the prevalence rate was up to 20%-90% in China.

In short, WMSDs not only seriously affects workers' personal health and work efficiency, but also leads to increasing the cost of enterprises such as absenteeism, loss of production line productivity, medical treatment, and compensation for workers and even affects the productivity of labor and imposes overall health care costs in the whole country. Studies have shown that WMSDs is a second-high incidence of occupational diseases only next to occupational mental illness because of its huge economic loss every year. At present, a number of scholars have carried out a series of related studies on WMSDs [18–23]. Lukman et al. indicated that drivers who performed MMH of heavy loads and adopted awkward postures are at a higher risk of developing WMSDs [19]. Celik et al. demonstrated that it is very important that working environment should be ergonomically arranged in order for office workers not to suffer WMSDs [20]. The results showed that WMSDs have become an important factor that cannot be ignored in the work environment and operation design.

As Nur et al. described in his study, the trend in modern industry is moving towards more time-intensive production with standardized, short cycle times and limited completion times at present [24]. We still consider how to improve productivity from these points of time, cost, and other factors directly related to production rather than energy consumption, employee fatigue, and other factors related to ergonomics.

In fact, some scholars have pointed out that there is a correlation between productivity and ergonomics [14]. Battini et al. demonstrated a link between them in assembly systems, where including ergonomics evaluations in the human operations analysis is a win-win approach due to the interaction between productivity, motion efficiency, and operational safety [25]. In Toole's study about architectural design, he pointed out that the most effective way to prevent WMSDs was to consider human factors at the design stage [26]. Fredericks et al. conducted two laboratory experiments to provide guidelines for ergonomic, which can reduce the risk of injury [12]. Otto and Scholl declared that ergonomic risks at the workplace cause a lot of damage on health and quality of life of workers [27]. Generally speaking, if industries are forced to pay attention to the physical comfort of workers in working environment at present, it can in turn lead to increased efficiency of the industry [28]. Improvement in ergonomics can contribute to improved performance and quality to make worker prevent WMSDs in the long-run [13]. Accordingly, ergonomics can not only reduce the risk of WMSDs, but also improve work performance and quality. Therefore, in order to prevent WMSDs caused by fatigue in engineering, managers should consider productivity and ergonomics comprehensively and design good working environment and operation to eliminate fatigue so as to achieve a win-win goal.

To the best of the authors' knowledge, there are a lot of researches on ergonomics, while they mainly used a single objective. Only a few papers considered ergonomic and economic issues comprehensively in evaluating MMH. One example is the work of Battini et al., which developed a new multiobjective model for solving assembly line balancing problem in order to include also the ergonomics aspect [18]. The authors created a set of tables, called the Predetermined Motion Energy System (PMES) that the model of Garg has been further developed. It can be used for energy estimation to reduce the time spent in calculating measures. However, they did not consider variables in analysis which can influence the energy consumption such as the number of input materials and process scheduling. Another article, written by Andriolo et al., proposed another multiobjective model that considers ergonomic aspects of MMH by using a lifting index (LI), rather than the model of energy consumption [29]. Calzavara et al. proposed an integrated planning approach that considers both economic and ergonomic objectives in order picking design by using energy consumption [13]. They directly solved the problems of ergonomics in various fields through the different mathematical models constructed in common. However, with the development of simulation software for ergonomics, we can use simulation technology to deal with the new biobjective model based intuitively and conveniently.

In addition, ergonomic simulation has been researched by many scholars. Many scholars have used mature ergonomic simulation software such as CATIA, JACK, IGRIP/ERGO, and other professional software to solve problems for enhancing efficiency and validity of ergonomics risk assessment in engineering [30–35]. Mazzola et al. said that Digital Human Model (DHM) has been developed in order to increase the level of quality of the ergonomic design process [30]. Fritzsche indicated that DHM simulation provides good ergonomics risk estimations of the workload in real-life task and matches real-life assessments obtained on a car assembly line [31]. They demonstrated that simulation approach is successfully used in improving participatory ergonomic work [32–35].

However, there are still little simulation researches on MMH, though they are becoming increasingly important in practice. Sundin and Medbo showed that 3D CAD visualization was successfully used in improving participatory ergonomic work about MMH at a Volvo plant in Sweden [36]. Ziaei et al. used rapid upper limb assessment (RULA) to assess the risks of awkward postures and estimate the forces and moments by computer-aided three-dimensional interactive application [37]. Li et al. proposed a methodology to use three-dimensional skeletal modeling to imitate workers movement in an actual construction manufacturing plant for lifting task [38].

In addition, it is rare to combine the biobjective model and simulation technology in the literature. To close this gap, we address this important question in the present study. In order to consider two aspects of productivity and ergonomics comprehensively, we construct a new biobjective mathematical model in order to design and evaluate MMH in which the handling time and the energy consumption are considered.

In this study, for the first time in the literature, we design and develop the interactive simulation platform to analyze two factors based on the openness of IGRIP/ERGO combined with MATLAB. Then, we analyze the numerical example about handling operations in an automobile brake pad manufacturing company illustrating both the proposed biobjective approach and the application of the interactive simulation platform. In the end of the study, we provide a deep parametric analysis according to the variations: change rate of energy-time ratio (ET) in order to design and evaluate MMH. As will be shown below, the methods can provide the win-win optimal solution for decision makers to make production environment and operation design in accordance with ergonomics and avoid or reduce the risk of WMSDs eventually.

The remainder of the study is structured as follows. The next section reviews related work on the job and describes the existing problem on the process flow with only minimum standard time and necessary assumptions. Section 3 develops in detail the biobjective formulations. Section 4, a numerical example based on a real case study is used, illustrating both the proposed biobjective approach and the application of the interactive simulation platform, and a deep parametric analysis is provided for decision makers to solve this problem in a real-life context. Finally, Section 5 draws several main conclusions to summarize the contribution and discusses some limitations of this study.

2. Problem Description

At present, manufacturing enterprises are mainly based on flowline manufacturing systems in 24 hours of mass production with four characteristics of fixed speed, continuity, fixed position, and fixed operation. The movement of production materials is mainly conveyed by conveyor belts, and employees assist machines in producing according to designed process routes and production rhythm [39]. In the design stage, the core is to minimize standard time, and flowline manufacturing systems further increase labor intensity of workers. It can be seen that there are some defects in designing the process flow with only minimum standard time, ignoring the health and safety of employees and increasing the risk of WMSDs, which is necessary to consider comprehensively.

To reduce the risk in modern industry, various ergonomic methods and tools have been developed in the past years to managers in evaluating ergonomic issues: self-assessment evaluation, video recordings methods or software tools to compute ergonomics indexes (REBA, RULA, OWAS, etc.), electromyography analysis (EMG), and spectroscopy-derived measures [40–44]. At present, the ergonomics evaluation method of MMH is energy consumption prediction model proposed by Garg from University of Michigan in US, which is widely used internationally [45].

This model has been widely used in many fields, such as agriculture and industry [6, 18, 25, 46, 47]. Battini et al. used the model in order to estimate the ergonomics level, which helps estimate the energy expenditure values for solving assembly line balancing problem [18]. In another literature, Battini et al. integrated energy expenditure into the storage assignment problem about order picking [25]. Li et al. indicated that a strong correlation was demonstrated between actual and predicted energy expenditure, suggesting the applicability of using the predictive equations of Garg et al. when they investigated actual responses in Chinese construction workers performing combined MMH [6]. Alkan et al. presented a low cost solution based on the prediction model used for virtual manufacturing process planning to enable optimization of assembly operations and workload capabilities at early design stage [47].

The prediction model divides the energy consumption into two categories: each activity of tasks and body postures; namely, the whole energy consumption can be estimated by summing up two types of energy consumption. The model is similar to the traditional time estimation method, such as predetermined motion time systems (PTMS), where the total time of the task is equal to the sum of the standard prediction time and some special task time [18]. Energy consumption is an important indicator of the degree of fatigue of workers about MMH, where the total energy consumption required to complete a task is equal to the sum of the energy consumed by single tasks. Since the increase in workload will lead to a significant increase in energy consumption, workers will be prone to fatigue. When energy consumption required is higher than that of the maximum capability of workers, it would lead to a risk of WMSDs [24].

In addition, some scholars pointed out that fatigue can degrade workers performance on tasks in production reflected by the change of task duration [48–52]. Digiesi et al. showed that workers spend more time to process jobs when they become tired and slower [49]. Ferjani et al. used a new methodology about workers fatigue, an adaptable dynamic assignment heuristic, to solve multiskilled workers assignment problem in the manufacturing system state [52]. In particular, the authors indicated that fatigue can increase the processing times of jobs; namely, workers may need more time than expected to process their tasks. They focused on the assignment of workers to the machines, computing more realistic task duration via taking the impact of workers fatigue into account. In the meantime, they assumed that parts may accumulate in the machine queues, causing the waiting time for jobs waiting for these queues to increase, which can have an impact on workers fatigue. However, there is a difference in calculating the total process time between single worker and workers affected by fatigue. Let us note that, since our main objective is the win-win optimal solution about single worker and two research objects, the number of input materials and process scheduling, we do not pretend to address the problem based on accurate task processing times. And we assume that the amount of input materials does not accumulate in queues to affect subsequent production, because conveyor belts can play roles of temporary storage areas. Therefore, we will pay attention to building a new biobjective model and develop the interactive simulation platform based on economics and ergonomics where processing times of single task are defined in advance.

From the studies presented above, we estimate the energy consumption based on this prediction model introduced by

Garg's model as the primary mathematical model to evaluate workload. In particular, we divide the energy consumption into two new categories: walk from workstation i to j and each operation in workstation i. Similarly, we divide the handling time into two new categories: walk from workstation i to j and each operation in workstation i in the next section.

In production, employees need to assist machines in producing at workstations such as raw material handling, parts assembly, semifinished measurement, finished packing, etc. Because of extensive popularization of 5S, the location of materials and articles in this factory is made clearly by the yellow line. The storage areas of raw materials and products needed for each production line are close to conveyor belts, but there are differences in height about the vertical direction and horizontal direction, where MMH is needed for employees.

It is assumed that materials have been tested by quality inspectors before being used. Accordingly, it does not need to consider the waste. In the meantime, the number of raw materials that employees input determines the number of the same parts and the number of finished products in the follow-up. Conveyor belts can play roles of temporary storage areas in the above so that subsequent production will not be influenced by the amount of input materials. Nevertheless, it can affect the time of a single process and total time workers required. Also, it will influence the average energy consumption of workers. In addition, different processes determine working paths of employees, which will also impact the value of their energy consumption.

Based on the assumptions stated above, and for the number of input materials and processes in terms of different situations, the biobjective models are developed that minimize two objective functions in the following: total handling time and total energy expenditure.

3. Model Development

3.1. Definitions

Decision Variable

q: total number of input materials

X_{ij}: process scheduling from workstation i to j

Time Notations

G: grade of the walking surface

S: walking speed

I: workstation collection of workers

n: total number of workstations

h_1: vertical height about start point of lifting or end point of lowering

h_2: vertical height about start point of lowering or end point of lifting

Δh: vertical distance of movements

Δd: horizontal distance of movements

T: cycle time

N: total number of cycle times

T_{ij}: time required for movement from workstation i to j

T_i: time required for single operation in workstation i

Energy Notations

BW: body weight

L: weight of the load

S: gender; 1 for males, 0 for females

E: total energy expenditure

E_{ij}: energy expenditure required for movement from workstation i to j

E_i: energy expenditure required for single operation in workstation i

E_{task}: energy expenditure required for single task

$E_{\text{pos}} = K_{\text{pos}} * BW$: energy expenditure required for each posture

K_{pos}: energy expenditure coefficient of each posture (sitting 0.024, standing 0.023, standing and bent position 0.028)

T_m: time duration of mth posture (m=1, 2, 3)

3.2. Model Building. In order to study the biobjective problem, we set up two objective functions for minimum handling time and minimum energy consumption:

$$\min T = \min \left[\sum T_{ij} + \sum_{i=1}^{n} \left(T_i * \mathrm{q} \right) \right] \tag{1}$$

$$\min E = \min \left[\sum E_{ij} + \sum_{i=1}^{n} \left(E_i * q \right) \right] \tag{2}$$

where

$$E_i = \min \left[\sum_{i=1}^{\mathrm{n}} E_{task} + \sum_{j=1}^{m} \left(E_{pos} * t_j \right) \right] \tag{3}$$

$$\sum_i \sum_j x_{ij} = 1$$

$$x_{ij} = \begin{cases} 1 & \text{if workers from station } i \text{ to } j \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$\begin{gathered} I = \{1, 2, \dots, n\} \\ T \geq 0, \; i = 1, 2, \dots, n, \; j = 1, 2, \dots, n \\ E \geq 0, \; i = 1, 2, \dots, n, \; j = 1, 2, \dots, n \\ \mathrm{q} > 0 \\ \mathrm{n} > 0 \end{gathered} \tag{5}$$

The biobjective function that we propose to minimize is thus formulated as

$$\min(T,E) = \min\left(\sum_{i=1}^{n} T_{task} + \sum_{j=1}^{m}\left(T_{pos} * \mathrm{q}\right), \sum_{i=1}^{n} E_{task} + \sum_{j=1}^{m}\left(E_{pos} * t_j\right)\right) \quad (6)$$

We define the optimal points T^0 and E^0 as the solutions of the single objective functions modeled by (1) and (2). Using the points, we can obtain $\overline{T}$ and $\overline{E}$ by (1) and (2), which are change rates of single objective solution functions. Then, we apply the called weighted sum method to (9), which is one of the most common approaches in biobjective optimization:

$$\overline{T} = \frac{\sum T_{ij} + \sum_{i=1}^{n}\left(T_i * \mathrm{q}\right) - T^0}{T^0} \quad (7)$$

$$\overline{E} = \frac{\sum E_{ij} + \sum_{i=1}^{n}\left(E_i * q\right) - E^0}{E^0} \quad (8)$$

$$\min(U) = \min\left(\alpha_1 * \overline{T}, \alpha_2 * \overline{E}\right) \quad (9)$$

where

$$\alpha_1 + \alpha_2 = 1; \quad \alpha_1, \alpha_2 \geq 0 \quad (10)$$

Traditionally, the minimum handling time determines the process route and takt time in the optimal production line. In turn, if the objective is to minimize energy expenditure of the MMH process, the optimal production line is designed by the minimum energy consumption. Alternatively, there are two special cases in the model that are $\alpha_1 = 1$, where only the minimum handling time is considered as an objective, and $\alpha_2 = 1$, where only the minimum energy consumption is considered in the optimization.

3.3. Model Solution. The difference between the biobjective problem and the single objective problem is that the optimal solution for a biobjective problem is not only a single optimal solution. The solutions exist in the set of nondominated optimal solutions, which is called the Pareto solution set. When a single target is improved, the performance of other subgoals will be reduced. Therefore, the approach to solve the biobjective problem is to balance and compromise among the subtargets. In recent years, more and more researchers have used genetic algorithms to solve biobjective or multiobjective optimization problems, which may have problems of computational complexity and slow speed [53, 54]. The most used method is the weighted sum method in many optimization methods whose mathematical modeling is simple and understood easily [55]. In this paper, we transform the biobjective problem into two single objective problems by using the weighted sum method and use the simulation technique to solve the problem as well. The solution steps are as follows.

Step 1. We gather the basic information of n workstations, workplace layout, and the input material in the production line by means of investigation and so on. Then the initial data operation is carried out. At the same time, the information of the staff and actual operation data are also collected such as body, weight, gender, and age.

Step 2. We determine parameters of the two-target model and establish a mathematical model based on the data obtained.

Step 3. We build the 3D simulation model on the platform of IGRIP/ERGO simulation software and design detailed parameters about process routes and energy consumption.

Step 4. We design and develop the interactive simulation platform based on the openness of IGRIP/ERGO combined with MATLAB, and program language is automatically generated. On this platform, interactive simulation and data analysis are carried out to obtain the handling time and energy consumption of different numbers of input materials and combinations of process routes.

Step 5. We obtain the optimal solution by using the weighted sum method.

The simulation process is shown in the diagram presented in Figure 1.

Table 1: Basic information of the worker.

	gender	age	height(cm)	body weight(kg)
worker	male	35	175	75

4. Case Analysis

In this paper, we set up a bivariate model about the number of input material and process routes considering the handling time and energy consumption of workers. The following case study is used to verify the effectiveness of the model. There are 25 production lines in an automobile brake pad manufacturing company, where each production line produces different types of workpieces. However, three core production lines generate 85% of the total profits for this company. The production process of certain core line mainly includes cutting, drilling, grinding, measuring, assembling, spraying, and marking. In this line, there are 13 machines and five workstations which require human interventions. The production line is shown in Figure 2.

In production, the employee handles rough blanks that underwent heat treatment from the storage area to the starting conveyor belt one by one (Workstation 1). Then he put fixers into the middle conveyor belt (Workstation 2). Next, he carries rings and warnings needed to the production line, respectively (Workstations 3 and 4). Finally, he transports the finished products to the packing area from the finishing conveyor belt (workstation 5). Due to the capacity limitation of conveyor belts, the range of q is [5, 20]. In addition, the basic information of workers and 5 workstations in the production line are shown, respectively, in Tables 1–3.

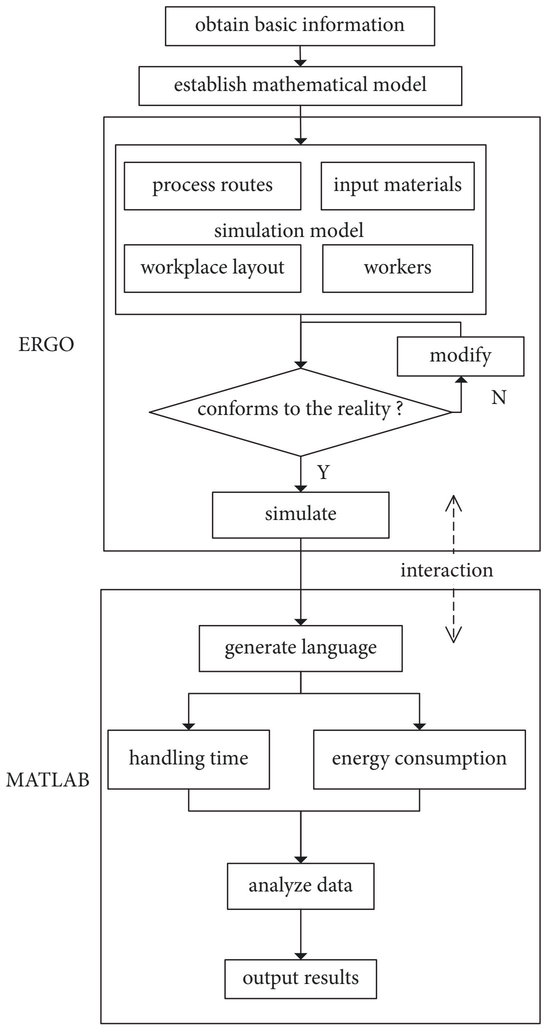

Figure 1: Flow of simulation.

Table 2: Basic information of workstations.

task	load weight (kg)	operation time (s)	total energy expenditure (kcal)	average energy expenditure (kcal/min)
rough blanks	16	9.6326	1.3742	8.5595
fixers	1	9.3472	0.8827	5.6722
rings	2	9.3078	0.9137	5.8899
warnings	1	9.4821	0.8966	5.6102
finished products	17	9.4883	1.3421	8.4867

Because the number of input materials is different, the cycle time is not easy to compare. However, the analysis of handling time about the single workpiece and the average energy consumption for the nonstop production line is to facilitate studying. As mentioned above, we solve it according to the concrete steps of the model.

Simulation software can provide good ergonomics risk estimations of the workload in real-life task and match real-life assessments [31]. In this simulation software we mentioned, IGRIP/ERGO is an interactive 3D simulation analysis tool of ergonomics which is suitable for design of workplace and improvement of work environment as a professional tool for human movement and tasks. Therefore, we build the simulation model for this production line. Figure 3 shows the simulation model based on IGRIP/ERGO software. Then, the interactive simulation platform is designed and developed based on the openness of IGRIP/ERGO, and the two-way communication line is created in the way of socket with MATLAB. The transfer of commands between the client and the server with TCP/IP can ensure the real-time and interactive performance of the simulation to achieve the purpose of transmitting data quickly and accurately. In addition, Graphic Simulation Language (GSL) can be automatically generated on the simulation platform, which simplifies operation process and improves efficiency and accuracy of simulation. Finally, the platform uses the Command Line Interpreter (CLI) to interact with MATLAB for data analysis in Figures 4 and 5.

Table 3: The distance between workstations (unit: m).

	1	2	3	4	5
1	-	8.47	9.46	3.16	1.37
2	8.47	-	5.35	6.05	7.87
3	9.46	5.35	-	6.30	8.25
4	3.16	6.05	6.30	-	2.05
5	1.37	7.87	8.25	2.05	-

The results clearly show that as load weight increases, the energy consumption of workers at MMH also increases. As Drain et al. suggested in his study, it is well established that as load weight increases, the energy consumption also increases when they evaluated a maximum acceptable work duration model about physically demanding occupations such as military and firefighting [56]. Gao et al., after comparing the metabolic effect of three different load carrying methods, concluded that metabolic cost increases with heavier load [57]. It is in agreement with studies that indicate the energy consumption increases linearly with loads weight [58]. As illustrated in Figure 6, the energy consumption is influenced by gender, body weight, and load weight, while there may be a linear relationship between load weight (L) and energy consumption (E).

The diagram of the relationship between percentages of change rate about E and T and the amount of input materials in the current sequential process route is shown in Figure 7. It is obvious that the value of energy consumption is greatly influenced by the quantity, while the value of handling time about the single workpiece is affected very little. Therefore, an appropriate increase in the amount of input materials can significantly reduce energy consumption without changing the process, which means that the travel distance for the operator remains constant, but there is a nonlinear relationship between them. In addition, as mentioned above, the energy consumption of MMH (E_i) will increase when load weight increases. As expressed in (2), this formula includes two factors: the energy consumption of task (E_i) and the energy consumption of movement (E_{ij}). The importance of

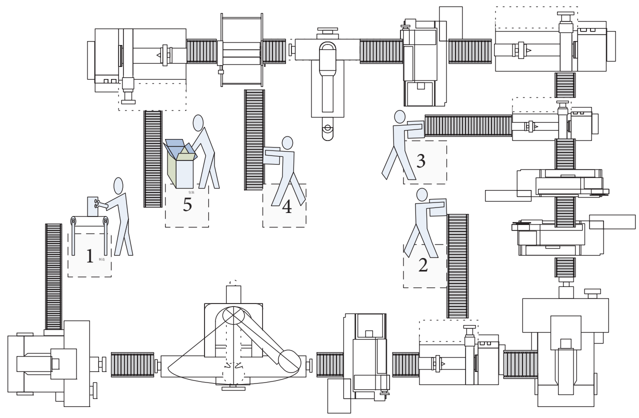

Figure 2: Diagram of the production line.

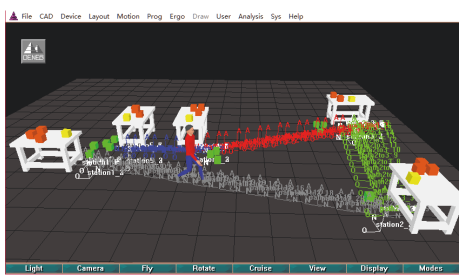

Figure 3: Simulation diagram of the model.

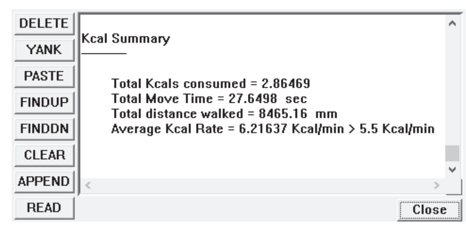

Figure 5: Simulation results from ERGO.

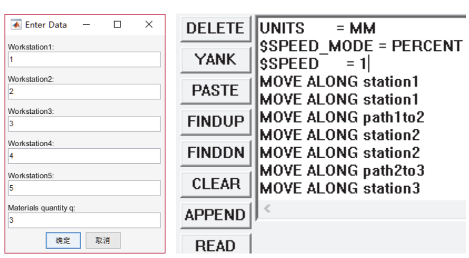

Figure 4: GSL generated from MATLAB.

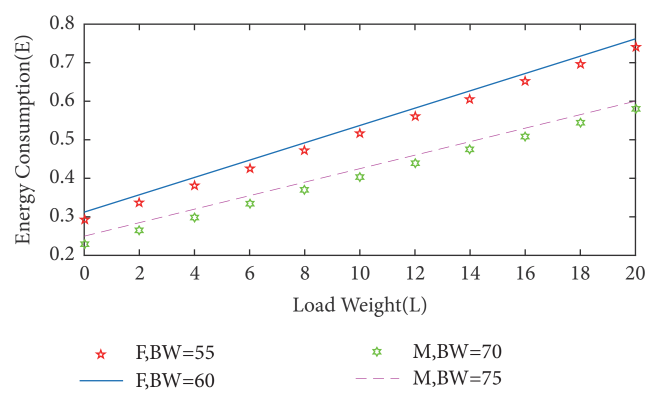

Figure 6: Effect factors of energy consumption.

both factors for the value of total energy consumption is a negative correlation. Accordingly, it will have more influence on the energy consumption for the operator when the activity that the operator has to perform is heavy, which implies the influence of the energy consumption on the travel distance (E_{ij}) becomes smaller for the operator.

In a next step, the Pareto frontiers are analyzed about varying values of the total number of input materials variable in Figure 8 (q = 5, 10, 15, 20). It shows the comprehensive impact of each process route and the number of input materials on the E and T. In this diagram, each point represents the percentage of the change rate compared to the minimum value of E and T in a particular process route. It can be seen that the differences in the percentage of change rate between E and T is similar when the amount of q is changed under different process routes. However, the smaller the amount of input materials is, the greater the impact of process route is on energy consumption and handling time, which is because distance differences between workstations have a great influence on them at the moment. As the number of q is increasing, the impact of distance differences is getting smaller and smaller. As stressed in Gebennini et al., the time spent travelling on foot from one station to another station, such as the operators' walking time, results in an unproductive time, and excessive walking might cause injuries and undue fatigue [59]. Accordingly, it is possible to reduce waste of the energy consumption by minimizing the energy spent by the operators in moving on foot from one station to another.

Regarding the optimal solution for the time-based and energy-based single objective models formulated in (1) and (2), we can consider two optimal cases, respectively. Taking

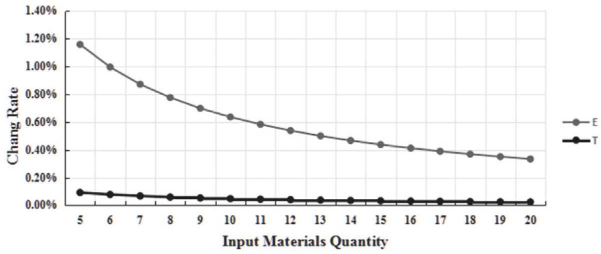

Figure 7: Change rate of E and T about certain procedure.

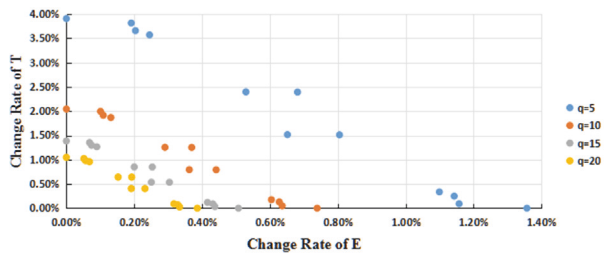

Figure 8: Change rate of E and T influenced by materials quantity.

Table 4: Handling time and energy consumption about solutions.

scheme	1	2	3	4
material quantity	19	15	8	6
process route	13254	12354	14235	13425
handling time(s)	48.6560	49.0322	50.1831	52.0872
energy consumption (kcal/min)	6.7854	6.7635	6.7091	6.6371

q = 5 as an example, it can be seen that the maximum difference is about 1.36% in time and 3.91% in energy from the change ratio of T and E in different process routes. In fact, handling time within the energy-based process route is 1.36% higher than the time that results if the time-based model is employed. Similarly, energy expenditure in using the time-based process route is 3.91% higher than for the solution that results for the energy-based model. According to [60], the reasonable weights of α_1 and α_2 in (9) are determined, and four sets of values are set to be (0.1,0.9), (0.3,0.7), (0.7,0.3), and (0.9,0.1) respectively. Table 4 shows that four available solutions are four sets of the minimum handling time and the minimum energy consumption of the task.

In this situation, scheme 1 indicates that the value of a worker's single-piece handling time is the minimum (48.6560s), while the value of average energy consumption is the maximum (6.7854kcal/min). On the contrary, scheme 4 requires that the value of single-piece handling time is the maximum (52.0872s), while the value of average energy consumption is the minimum (6.6371kcal/min). In order to take account of the shortest handling time and the minimum energy consumption, a scheme with the min E is chosen as much as possible on the premise of meeting requirements of production. In this case, assuming that single-piece handling time is more than 50s, scheme 2 should be selected in four schemes. Not only the min handling time (49.0322s) can meet technological requirements, but also the energy consumption of the worker is the minimum (6.7635kcal/min).

5. Conclusions

In this paper, we construct a new biobjective mathematical model of handling time and energy consumption, where workers' fatigue is ignored about physiological factors in view of work environment and operation design of MMH in manufacturing enterprises, which can lead to problems of reducing production efficiency by WMSDs. The model is based on two aspects of production efficiency and ergonomics. According to our mathematical model, the minimum handling time and the minimum energy consumption are two objective functions. By using the linear weighted summation method, the biobjective problem is transformed into single objective problems, and the MMH is evaluated and designed. We research the number of input materials and process routes in the case analysis that can obtain a number of combination schemes for the process routes and the amount of input materials. Therefore, the model has multiple satisfactory solutions, which can provide various alternatives for managers. Managers can choose the best combination plan based on two aspects of economics and ergonomics to achieve the win-win goal.

In addition, we design and develop the new interactive simulation platform based on the openness of IGRIP/ERGO combined with MATLAB. Then, we analyze the case about MMH in an automobile brake pad manufacturing company and take the number of input materials and process scheduling as research objects. Data interaction and statistics are implemented based on this platform to study on handling time and energy consumption. In the meantime, the case study demonstrates that the interactive simulation platform can be devoted to providing the solution of modern production operation directly and conveniently, which can make the production environment and operation design in accordance with ergonomics and can effectively prevent and avoid the risk of WMSDs. However, this paper only takes into account the continuous operation of a single worker in a manufacturing line. In fact, the model will be more troublesome, but more practical if it can be extended to the factors about multiple workers and rest time based on the consideration of ergonomics.

Data Availability

The data used to support the findings of this study are available from the first author upon request.

Conflicts of Interest

The authors declared that there are no conflicts of interest in their submitted paper.

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References

[1] H. Mohammadi, M. Motamedzade, M. A. Faghih, H. Bayat, M. H. Mohraz, and S. Musavi, "Manual material handling assessment among workers of Iranian casting workshops," *International Journal of Occupational Safety and Ergonomics*, vol. 19, no. 4, pp. 675–681, 2013.

[2] H. R. Zadry, S. Z. M. Dawal, and Z. Taha, "Development of statistical models for predicting muscle and mental activities during repetitive precision tasks," *International Journal of Occupational Safety and Ergonomics*, vol. 22, no. 3, pp. 374–383, 2016.

[3] A. Reiman, A. Putkonen, N. Nevala, M. Nyberg, S. Väyrynen, and M. Forsman, "Delivery truck drivers' work outside their cabs: Ergonomic video analyses supplemented with national accident statistics," *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 25, no. 3, pp. 340–352, 2015.

[4] M. Erdem, F. E. Boran, and D. Akay, "Classification of Risks of Occupational Low Back Disorders with Support Vector Machines," *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 26, no. 5, pp. 550–558, 2016.

[5] D. Battini, C. H. Glock, E. H. Grosse, A. Persona, and F. Sgarbossa, "Ergo-lot-sizing: An approach to integrate ergonomic and economic objectives in manual materials handling," *International Journal of Production Economics*, vol. 185, pp. 230–239, 2017.

[6] K. W. Li, R.-F. Yu, Y. Gao, R. V. Maikala, and H.-H. Tsai, "Physiological and perceptual responses in male Chinese workers performing combined manual materials handling tasks," *International Journal of Industrial Ergonomics*, vol. 39, no. 2, pp. 422–427, 2009.

[7] S. Kim, M. A. Nussbaum, and B. Jia, "The benefits of an additional worker are task-dependent: Assessing low-back injury risks during prefabricated (panelized) wall construction," *Applied Ergonomics*, vol. 43, no. 5, pp. 843–849, 2012.

[8] H. Kim, J. Dropkin, K. Spaeth, F. Smith, and J. Moline, "Patient handling and musculoskeletal disorders among hospital workers: Analysis of 7 years of institutional workers' compensation claims data," *American Journal of Industrial Medicine*, vol. 55, no. 8, pp. 683–690, 2012.

[9] A. L. Schoenfsch, H. J. Lipscomb, L. A. Pompeii, D. J. Myers, and J. M. Dement, "Musculoskeletal injuries among hospital patient care staff before and after implementation of patient lift and transfer equipment," *Scandinavian Journal of Work, Environment & Health*, vol. 39, no. 1, pp. 27–36, 2013.

[10] E. Valero, A. Sivanathan, F. Bosché, and M. Abdel-Wahab, "Musculoskeletal disorders in construction: a review and a novel system for activity tracking with body area network," *Applied Ergonomics*, vol. 54, pp. 120–130, 2016.

[11] Y. Harari, R. Riemer, and A. Bechar, "Factors determining workers' pace while conducting continuous sequential lifting, carrying, and lowering tasks," *Applied Ergonomics*, vol. 67, pp. 61–70, 2018.

[12] T. K. Fredericks, A. R. Kumar, and S. Karim, "An ergonomic evaluation of a manual metal pouring operation," *International Journal of Industrial Ergonomics*, vol. 38, no. 2, pp. 182–192, 2008.

[13] M. Calzavara, C. H. Glock, E. H. Grosse, A. Persona, and F. Sgarbossa, "Analysis of economic and ergonomic performance measures of different rack layouts in an order picking warehouse," *Computers & Industrial Engineering*, vol. 111, pp. 527–536, 2017.

[14] E. H. Grosse and C. H. Glock, "The effect of worker learning on manual order picking processes," *International Journal of Production Economics*, vol. 170, no. 1, pp. 882–890, 2015.

[15] C. Nordander, G.-Å. Hansson, K. Ohlsson et al., "Exposure-response relationships for work-related neck and shoulder musculoskeletal disorders-analyses of pooled uniform data sets," *Applied Ergonomics*, vol. 55, pp. 70–84, 2016.

[16] E. Schneider and X. Irastorza, *OSH in Figures: Work-Related Musculoskeletal Disorders in the EU-Facts and Figures*, European Agency for Safety and Health at Work, Luxembourg City, Luxembourg, 2010.

[17] Bureau of Labor Statistics, *Nonfatal Occupational Injuries and Illnesses Requiring Days away from Work*, U.S. Department of Labor, Washington, DC, USA, 2008.

[18] D. Battini, X. Delorme, A. Dolgui, A. Persona, and F. Sgarbossa, "Ergonomics in assembly line balancing based on energy expenditure: A multi-objective model," *International Journal of Production Research*, vol. 54, no. 3, pp. 824–845, 2016.

[19] K. A. Lukman, M. S. Jeffree, and K. G. Rampal, "Low back pain and its association with whole body vibration and manual material handling among commercial drivers in Sabah," *International Journal of Occupational Safety & Ergonomics Jose*, pp. 1–18, 2018.

[20] S. Celik, K. Celik, E. Dirimese, N. Tasdemir, T. Arik, and İ. Büyükkara, "Determination of pain in musculoskeletal system reported by office workers and the pain risk factors," *International Journal of Occupational Medicine and Environmental Health*, vol. 31, no. 1, pp. 91–111, 2018.

[21] P. Arezes and F. Serranheira, "New approaches and interventions to prevent Work Related Musculoskeletal Disorders," *International Journal of Industrial Ergonomics*, vol. 60, pp. 1-2, 2017.

[22] S. Bulduk, E. Özgür Bulduk, and T. Süren, "Reduction of work-related musculoskeletal risk factors following ergonomics education of sewing machine operators," *International Journal of Occupational Safety and Ergonomics: JOSE*, vol. 23, no. 3, pp. 347–352, 2017.

[23] W. Shin and M. Park, "Ergonomic interventions for prevention of work-related musculoskeletal disorders in a small manufacturing assembly line," *International Journal of Occupational Safety and Ergonomics: JOSE*, pp. 1–13, 2017.

[24] N. M. Nur, S. Z. M. Dawal, M. Dahari, and J. Sanusi, "The effects of energy expenditure rate on work productivity performance at different levels of production standard time," *Journal of Physical Therapy Science*, vol. 27, no. 8, pp. 2431–2433, 2015.

[25] D. Battini, C. H. Glock, E. H. Grosse, A. Persona, and F. Sgarbossa, "Human energy expenditure in order picking storage assignment: a bi-objective method," *Computers & Industrial Engineering*, vol. 94, no. 1, pp. 147–157, 2016.

[26] T. M. Toole and J. Gambatese, "The Trajectories of Prevention through Design in Construction," *Journal of Safety Research*, vol. 39, no. 2, pp. 225–230, 2008.

[27] A. Otto and A. Scholl, "Incorporating ergonomic risks into assembly line balancing," *European Journal of Operational Research*, vol. 212, no. 2, pp. 277–286, 2011.

[28] R. T. Vyavahare and S. P. Kallurkar, "Ergonomic evaluation of electric hedge trimmer using digital human modeling," *Agricultural Engineering International: CIGR Journal*, vol. 17, no. 4, pp. 100–108, 2015.

[29] A. Andriolo, D. Battini, A. Persona, and F. Sgarbossa, “A new bi-objective approach for including ergonomic principles into EOQ model,” *International Journal of Production Research*, vol. 54, no. 9, pp. 2610–2627, 2016.

[30] M. Mazzola, L. Forzoni, S. D. Onofrio, and G. Andreoni, “Use of Digital Human Model for ultrasound system design: a case study to minimize the risks of musculoskeletal disorders,” *International Journal of Industrial Ergonomics*, vol. 60, no. 1, pp. 35–46, 2017.

[31] L. Fritzsche, “Ergonomics risk assessment with digital human models in car assembly: Simulation versus real life,” *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 20, no. 4, pp. 287–299, 2010.

[32] A. Golabchi, H. SangHyeok, S. JoonOh, H. SangUk, L. SangHyun, and M. Al-Hussein, “An Automated Biomechanical Simulation Approach to Ergonomic Job Analysis for Workplace Design,” *Journal of Construction Engineering Management*, vol. 141, no. 8, pp. 1–12, 2015.

[33] E. Álvarez-Casado, B. Zhang, S. T. Sandoval, and M. Pedro, “Using ergonomic digital human modeling in evaluation of workplace design and prevention of work-related musculoskeletal disorders aboard small fishing vessels,” *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 26, no. 4, pp. 463–472, 2016.

[34] R. L. Greene, D. P. Azari, Y. H. Hu, and R. G. Radwin, “Visualizing stressful aspects of repetitive motion tasks and opportunities for ergonomic improvements using computer vision,” *Applied Ergonomics*, vol. 65, pp. 461–472, 2017.

[35] O. Akkas, C. H. Lee, Y. H. Hu, C. Harris Adamson, D. Rempel, and R. G. Radwin, “Measuring exertion time, duty cycle and hand activity level for industrial tasks using computer vision,” *Ergonomics*, vol. 60, no. 12, pp. 1730–1738, 2017.

[36] A. Sundin and L. Medbo, “Computer visualization and participatory ergonomics as methods in workplace design,” *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 13, no. 1, pp. 1–17, 2003.

[37] M. Ziaei, H. Ziaei, S. Y. Hosseini et al., “Assessment and virtual redesign of a manual handling workstation by computer-aided three-dimensional interactive application,” *International Journal of Occupational Safety and Ergonomics*, vol. 23, no. 2, pp. 169–174, 2017.

[38] X. Li, S. Han, M. Gül, M. Al-Hussein, and M. El-Rich, “3D Visualization-Based Ergonomic Risk Assessment and Work Modification Framework and Its Validation for a Lifting Task,” *Journal of Construction Engineering and Management*, vol. 144, no. 1, 2018.

[39] Y. Li, X. Li, and J. Gupta, “Solving the multi-objective flowline manufacturing cell scheduling problem by hybrid harmony search,” *Expert Systems with Applications*, vol. 42, no. 3, pp. 1409–1417, 2015.

[40] B. Das and G. Mabaleka, “An electromyographic investigation of asymmetric lifting and moving of a load: I. Effects of load lift from floor to target shelves,” *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 19, no. 3, pp. 254–274, 2009.

[41] S. A. Oyewole, “Enhancing ergonomic safety effectiveness of repetitive job activities: Prediction of muscle fatigue in dominant and nondominant arms of industrial workers,” *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 24, no. 6, pp. 585–600, 2014.

[42] M. A. Wahyudi, W. A. Dania, and R. L. Silalahi, “Work Posture Analysis of Manual Material Handling Using OWAS Method,” *Agriculture and Agricultural Science Procedia*, vol. 3, no. 1, pp. 195–199, 2015.

[43] Y. Labbafinejad, Z. Imanizade, and H. Danesh, “Ergonomic Risk Factors and Their Association with Lower Back and Neck Pain among Pharmaceutical Employees in Iran,” *Workplace Health and Safety*, vol. 64, no. 12, pp. 586–595, 2016.

[44] Y. K. Kong, S. Y. Lee, K. S. Lee, and D. M. Kim, “Comparisons of ergonomic evaluation tools (ALLA, RULA, REBA and OWAS) for farm work,” *International Journal of Occupational Safety and Ergonomics*, vol. 23, no. 2, pp. 218–223, 2018.

[45] A. Garg, D. B. Chaffin, and G. D. Herrin, “Prediction Of Metabolic Rates For Manual Materials Handling Jobs,” *American Industrial Hygiene Association Journal*, vol. 39, no. 8, pp. 661–674, 1978.

[46] S. Jena, A. Kumar, J. K. Singh, and I. Mani, “Biomechanical model for energy consumption in manual load carrying on Indian farms,” *International Journal of Industrial Ergonomics*, vol. 55, pp. 69–76, 2016.

[47] B. Alkan, D. Vera, M. Ahmad, B. Ahmad, and R. Harrison, “A lightweight approach for human factor assessment in virtual assembly designs: an evaluation model for postural risk and metabolic workload,” *Procedia CIRP*, vol. 44, pp. 26–31, 2016.

[48] J. Perez, M. P. D. Looze, T. Bosch, and W. P. Neumann, “Discrete event simulation as an ergonomic tool to predict workload exposures during systems design,” *International Journal of Industrial Ergonomics*, vol. 44, no. 2, pp. 298–306, 2014.

[49] S. Digiesi, A. A. A. Kock, G. Mummolo, and J. E. Rooda, “The effect of dynamic worker behavior on flow line performance,” *International Journal of Production Economics*, vol. 120, no. 2, pp. 368–377, 2009.

[50] E. J. Lodree Jr., C. D. Geiger, and X. Jiang, “Taxonomy for integrating scheduling theory and human factors: Review and research opportunities,” *International Journal of Industrial Ergonomics*, vol. 39, no. 1, pp. 39–51, 2009.

[51] S. Elkosantini and D. Gien, “Integration of human behavioural aspects in a dynamic model for a manufacturing system,” *International Journal of Production Research*, vol. 47, no. 10, pp. 2601–2623, 2009.

[52] A. Ferjani, A. Ammar, H. Pierreval, and S. Elkosantini, “A simulation-optimization based heuristic for the online assignment of multi-skilled workers subjected to fatigue in manufacturing systems,” *Computers & Industrial Engineering*, vol. 112, pp. 663–674, 2017.

[53] H. Tian, K. Li, and W. Liu, “A pareto-based adaptive variable neighborhood search for biobjective hybrid flow shop scheduling problem with sequence-dependent setup time,” *Mathematical Problems in Engineering*, vol. 2016, Article ID 1257060, 11 pages, 2016.

[54] C. Lu, L. Gao, X. Li, Q. Wang, W. Liao, and Q. Zhao, “An efficient multiobjective backtracking search algorithm for single machine scheduling with controllable processing times,” *Mathematical Problems in Engineering*, vol. 2017, Article ID 8696985, 24 pages, 2017.

[55] Y. Elahi and M. I. A. Aziz, “Mean-variance-CvaR model of multiportfolio optimization via linear weighted sum method,” *Mathematical Problems in Engineering*, vol. 2014, Article ID 104064, 7 pages, 2014.

[56] J. Drain, D. Billing, D. Neesham-Smith, and B. Aisbett, “Predicting physiological capacity of human load carriage-a review,” *Applied Ergonomics*, vol. 52, pp. 85–94, 2016.

[57] Z. G. Gao, S. Q. Sun, R. S. Goonetilleke, and D. H. K. Chow, “Effect of an on-hip load-carrying belt on physiological and

perceptual responses during bimanual anterior load carriage," *Applied Ergonomics*, vol. 55, pp. 133–137, 2016.

[58] S. Paul, D. Bhattarcharrya, T. Chatterjee et al., "Physiological and biochemical responses during incremental uphill load carriage," *International Journal of Industrial Ergonomics*, vol. 50, pp. 26–33, 2015.

[59] E. Gebennini, L. Zeppetella, A. Grassi, and B. Rimini, "Optimal job assignment considering operators' walking costs and ergonomic aspects," *International Journal of Production Research*, vol. 56, no. 3, pp. 1249–1268, 2018.

[60] X. S. Zhao, C. Y. Chang, Y. Zhang et al., "Work-Rest Scheduling to Consider Workers' Fatigue," *Industrial Engineering and Management*, vol. 17, no. 1, pp. 112–116, 2012.