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SIMULATION-BASED ANALYSIS OF OPERATIONAL EFFICIENCY AND SAFETY IN A VIRTUAL ENVIRONMENT

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ABSTRACT

Effective evaluation of the productivity and safety of manual operations is essential for successful planning of operations as well as for workplace design. However, actions employed by production planners to improve productivity might adversely impact the ergonomic safety of workers. To address this issue, methods and tools are required that enable simultaneous evaluation of the efficiency and safety of operations. Thus, this study proposes an approach that integrates predetermined motion time systems and ergonomic assessment into a discrete-event simulation environment, and uses inputs obtained from point cloud and 3D models of a workplace to analyze both the productivity and ergonomic safety of manual operations. The proposed approach facilitates the evaluation and improvement of efficiency and ergonomic safety of manual tasks by automating the analysis and eliminating the need for onsite measurements and observations, all without the need for extensive prior knowledge regarding how PMTSs and ergonomic assessment methods work.

1 INTRODUCTION

Due to the labor-intensiveness of the construction industry, and the key role workers play as one of the main resources in a project, effective modeling of manual operations is an essential factor in achieving the project goals efficiently. Labor performance and safety can be considered the two primary contributors to the effectiveness of manual operations. The performance of the workers is a critical element in the overall productivity of the operations, and, as labor cost can account for more than half of the costs of a project (Gomar et al. 2002), reliable estimation of duration of manual tasks is vital for effective planning and scheduling of operations. On the other hand, one of the primary goals of any project is to ensure that all operations are performed without risking the safety and well-being of workers. Considering the high number of physically challenging tasks in construction operations, ergonomic safety of workers should be a priority in any safety management strategy. Ergonomic injuries are considered the leading type of occupational disability (WHO 2003), accounting for 29% of lost-time work-related injuries in the United States (Chiasson et al. 2012).

While focusing mainly on improving the performance of manual operations in order to boost productivity, actions of production planners and engineers might adversely affect the ergonomic safety of the workers by imposing high biomechanical exposure (Wells et al. 2007). Meanwhile, ergonomists and occupational health and safety practitioners usually suggest interventions, such as slower pace of work and more rest allowances to allow for sufficient recovery of the human body, that might result in decreasing the productivity of the operations. Previous studies on the correlation between productivity and safety are shown to be indecisive (Hallowell 2011). While some studies have shown positive correlation between productivity and safety (Hare et al. 2006; Shikdar and Sawaqed 2003; McLain and Jarrell 2007), others indicate a negative relationship, especially in the short-term (Choudhry and Fang 2008; Probst and Brubaker 2007; Choi et al. 2006). Thus, there is a contradiction between improving productivity and safety while focusing on modifying aspects of work that are related to time (e.g., duration of tasks, idle time, duration of exposure) (Wells et al. 2007). In order to ensure design of safe and productive operations, tools and methods are required that enable simultaneous analysis of the efficiency and safety of manual operations by combining the time aspects of each.

Simulation modeling is a tool that enables analysis of operations by evaluating different scenarios of production and selecting the most feasible. In construction, discrete-event simulation (DES) has been used extensively and established as a reliable approach to analyzing complex and dynamic construction systems (Lu 2003). Figure 1 summarizes some of the applications of simulation in different phases of construction (Ozcan-Deniz and Zhu 2015; Zhou et al. 2009; Corona-Suárez et al. 2014; Yang et al. 2012).

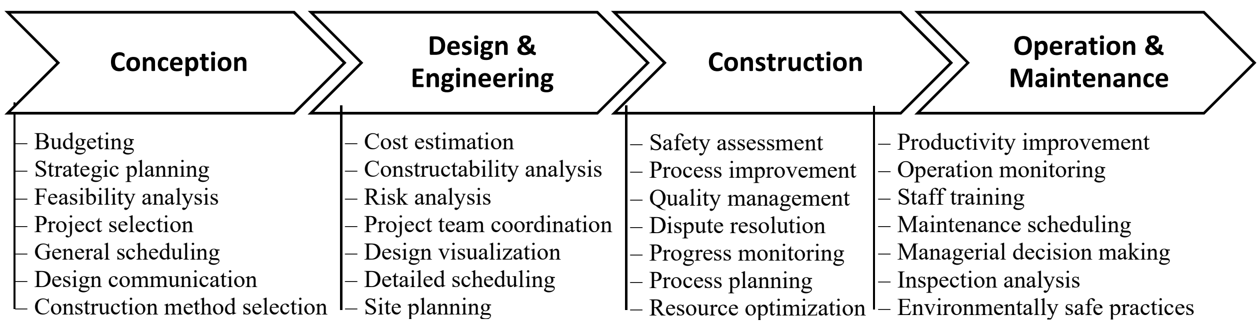


Figure 1: Applications of simulation modeling in different phases of construction.

Although many advances have been made in the use of simulation modeling for estimation of construction task duration, it has not been adapted to its full potential for modeling of manual construction operations (Golabchi et al. 2015b). In particular, DES can be useful in modeling manual tasks, as it enables modeling human operators as resources of the system and can be adjusted to generate appropriate information on time aspects of human work (e.g., active and idle time). Given that this type of information is not directly available from other pertinent modeling and analysis tools, DES can complement these methods to provide reliable analysis outputs without requiring detailed and extensive inputs. Furthermore, DES facilitates experimentation with different methods of carrying out manual tasks in order to select the optimal one. This study proposes a method that uses DES, in conjunction with Predetermined Motion Time Systems (PMTS) and ergonomic assessment, to enable design of productive and safe operations. Due to the importance of geometry information of the workplace, as well as the visualization of the working conditions for both efficiency and safety analysis purposes, the simulation is linked to a 3D representation of the working environment. This approach facilitates the analysis by reducing the time and effort required for data acquisition, and also ensures the accuracy of the required inputs.

2 CONCURRENT PRODUCTIVITY AND SAFETY ANALYSIS

This study integrates PMTS and ergonomic assessment with DES and uses 3D visualization of the working environment in order to obtain the required inputs for the analysis of the efficiency and ergonomic safety of manual operations. The framework of the study is shown in Figure 2. The visualization of the workplace is developed either by using point clouds, generated from photographs of the jobsite in the case of existing operations, or through the 3D design model of the working environment in the case of non-existing operations. This virtual representation enables measurement of the variables of the PMTS and ergonomics analysis (e.g., walking distance), as well as observation of the conditions of the working environment to acquire inputs that cannot be measured directly (e.g., posture). The simulation engine then runs the analysis based on the provided inputs, and outputs the results that are then used to evaluate and improve the efficiency and safety of the operations simultaneously.

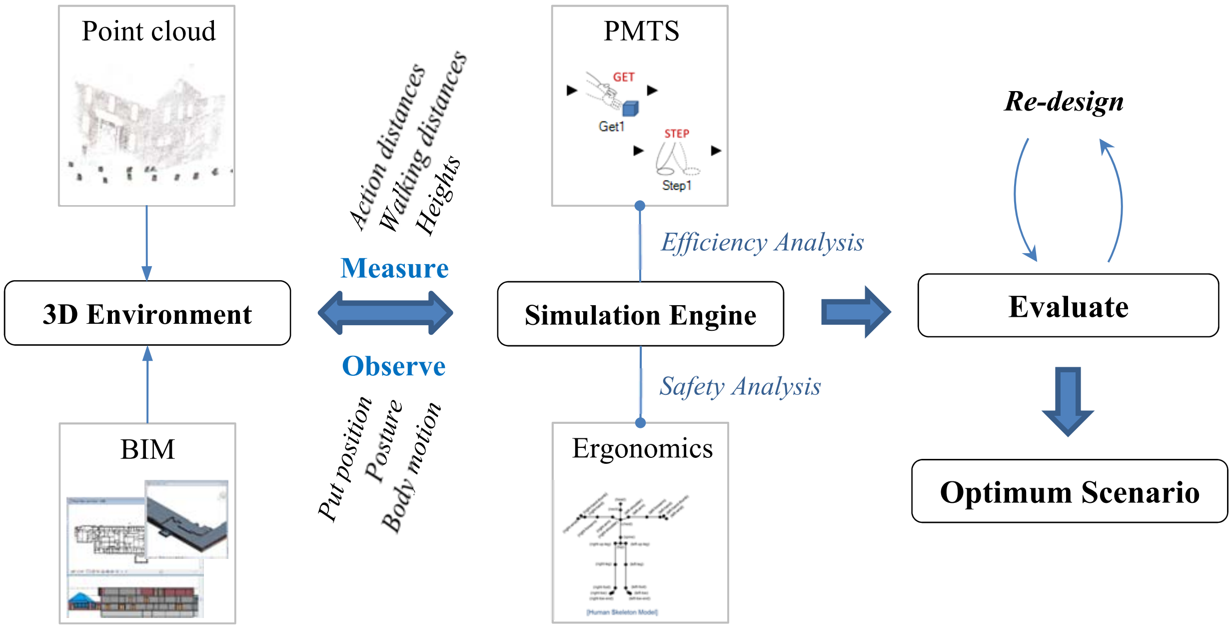


Figure 2: Framework of efficiency and safety analysis using 3D representation of workplace.

2.1 Visualization of Workplace

In order to perform reliable analysis of manual operations, data pertaining to workplace settings and conditions is required. This includes dimensions of the different elements of the workplace as well as shapes and geometries of objects. In the case of existing workplaces, measuring and observing these distances and working conditions requires significant time and effort, given that the existing conditions of construction workplaces change frequently. In the case of designing new operations, the lack of a reference model decreases the accuracy and reliability of the analysis, as it is difficult to perceive the design of a non-existing workplace and to assess the different alternatives. Thus, by using a 3D representation of the workplace, not only can the analysis be completed without the need of measurements and direct observations in the jobsite, but it also provides higher accuracy, requires less time and effort, and facilitates evaluation of ergonomic factors such as clearance, reach, and visibility.

With the recent advancements in generating and using point cloud data in construction (El-Omari and Moselhi 2008; Fathi and Brilakis, 2011), as well as transforming point clouds into 3D models (Tang et al. 2010; Bosche and Haas 2008), using this type of model can be very beneficial for obtaining the required inputs for efficiency and safety analysis. In the present study, an image-based 3D reconstruction method is employed that only requires simple photographs of a workplace as inputs; using a structure-from-motion algorithm, the photographs are converted to a point cloud of the working environment. Since conditions of construction jobsites change frequently, the simplicity of this approach enables a 3D representation of the current conditions of the workplace, as opposed to using as-designed 3D models which may not accurately reflect the current settings of the jobsite. In the case of non-existing workplaces, 3D design models of the workplace can be used as effectively. With the ongoing advancements in the use of Building Information Modeling (BIM) during design and construction as well as operation and management (Golabchi et al.

2016), this type of model can be highly useful for obtaining reliable data regarding the design of the workplace.

After creating the 3D virtual representation of the workplace, this representation is used to measure the required variables of the analysis and also to observe the conditions of the jobsite in order to facilitate the user's decision-making regarding selecting the values of the input variables. Furthermore, the 3D representation is used to explore the impact of different workplace designs on the productivity and safety of operations. By changing the design of the jobsite, the user can experiment with different scenarios and evaluate with high accuracy various options for operation design.

2.2 Efficiency Analysis

Reliable estimation of duration of manual activities is essential for effective planning and scheduling of operations. Accordingly, various approaches have been developed that provide time data for manual tasks based on the jobsite settings and working methods. PMTSs, considered one of the most effective methods (Genaidy et al. 1990), provide a standard duration for manual activities by describing the motions used to carry out an activity. Some of the primary PMTSs include Methods-Time Measurement (MTM) (Maynard et al. 1948), Maynard Operation Sequence Technique (MOST) (Zandin 1980), and Modular Arrangement of Predetermined Time Standards (MODAPTS) (Heyde 1966). While these tools are frequently used in other industries for evaluating and improving manual operations (Kuhlang et al. 2011; Gupta and Chandrawat 2012; Xu et al. 2013), less attention has been given to their potential applications in the construction industry.

For the purpose of this study, the MOST approach is integrated into the DES engine, which requires inputs describing the method whereby a manual task is carried out and which outputs a standard duration for the activity. The MOST method is selected due to its simplicity, effectiveness, and quicker application compared to other PMTS methods (Tuan et al. 2014; Patil et al. 2004; Zandin 1980). The required inputs for a general move sequence model of MOST, which can be used to describe any movement activity, are shown in Table 1. The algorithm behind the DES engine calculates a duration for each of the manual activities involved in the operation design, based on the principles of the MOST and the inputs selected for each of the variables.

Table 1: Variables of the general move sequence model in MOST.

Variable	Description	Example of possible values
Action Distance	Any spatial movement or action of the fingers, hands, and feet.	Within reach, 1-2 steps, 3-4 steps
Body Motion	Vertical motions of the body or actions required to overcome an obstruction.	Bend and arise, sit or stand
Gain Control	Motions used to obtain control of an object.	Light object, heavy or bulky
Place	Motions involved in placement of an object.	Toss, precision, light pressure

The action distance variable is an example of an input that can be obtained through direct measurements in the 3D model. For example, the distance worker walks to carry a concrete block is an example of a variable that can be measured from the point cloud or 3D model by selecting the start and end positions. The body motion, gain control, and placement are examples of variables that can be obtained by observing the conditions of the workplace through the virtual model. For example, by looking at the final destination of a concrete block, the user can decide whether the placement task will be carried out without adjustments or with precision. Furthermore, integrating PMTS methods such as MOST into the simulation engine enables quicker application and requires significantly less user training time compared to manual analysis, since the process is automated.

2.3 Ergonomic Safety Analysis

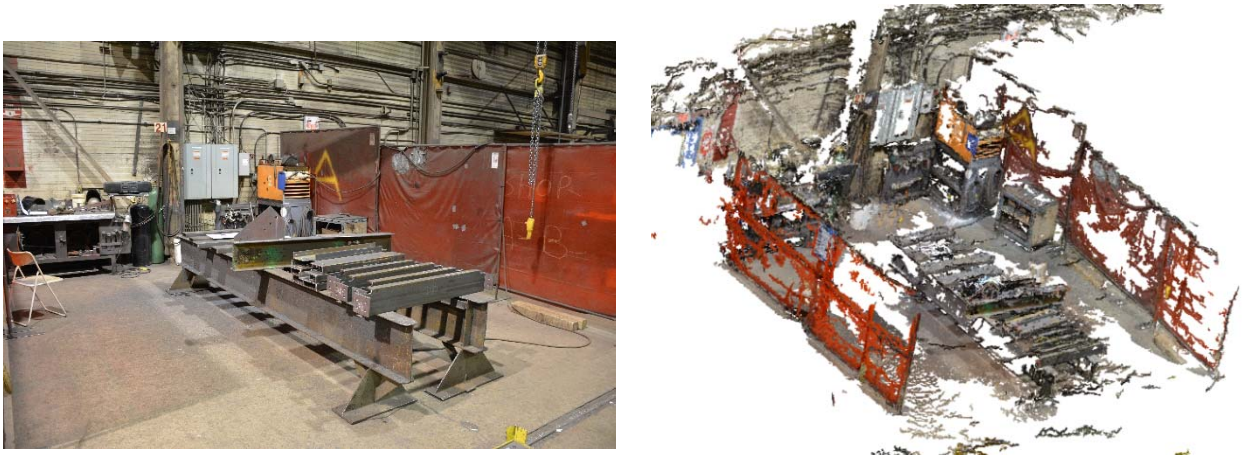
Various ergonomic analysis tools have been developed that aim to identify unsafe actions and prevent Work-related Musculoskeletal Disorders (WMSDs). Considering the prevalence of WMSDs in the construction industry, using these tools in the design of manual tasks can effectively reduce the rate of these injuries. For the purpose of this study, the Ovako Working Posture Analysing System (OWAS) (Karhu et al. 1977) is used as an example of an effective ergonomic assessment work-study approach, suitable for analyzing manual construction tasks (Kivi and Mattila 1991). OWAS categorizes postures of different body parts and assigns a score to each posture. The postures of back are shown in Figure 3 as an example. After assigning the observed posture to one of the posture categories for each body part and selecting the appropriate load (e.g., less than 10 kg, between 10 and 20 kg), the overall risk score of the task is computed. Furthermore, by calculating the number of times a risk category for each body part has occurred, OWAS provides a score for each specific body part which indicates the level of risk of the whole operation for that body part.

Figure 3: OWAS posture categories for back.

The OWAS method is integrated into the simulation engine, in conjunction with the PMTS analysis, to provide the level of ergonomic risk of a manual task. By extracting the required inputs of the OWAS analysis from the virtual representation of the jobsite, the DES engine calculates the corresponding OWAS score and reports on the required corrective plan of action (e.g., no action required, immediate intervention required). This information is used to change the design and examine its impact on the safety of the manual activity to ensure all tasks are designed within the allowable level of risk.

3 PROOF OF CONCEPT

In order to implement the proposed framework, a manual construction task is modeled and analyzed. The manual task involves a worker handling steel beams as part of a production system in a steel fabrication shop. Tasks similar to the one modeled here are critical as they have a significant impact on the efficiency of the operations as well as a potentially high level of ergonomic risks. Figure 4(a) shows the workstation of the steel plate handling task. The manual task includes a worker picking up sections of steel beams from the floor and placing them on the worktable to prepare them for welding. Since the workstation is an existing one, photographs are taken from the workstation and, using the VisualSFM (Wu 2011) algorithm, the corresponding point cloud is created (Guo et al. 2016), as shown in Figure 4(b). As mentioned above, in case of new workplaces, the 3D or BIM model of the workplace is used instead of the point cloud model.



(a) (b)

Figure 4: Workstation of steel plate handling task, (a) photograph, and (b) corresponding point cloud.

After creating the point cloud model, the model is used to estimate the required inputs for the efficiency and safety analysis. Since the workplace conditions need to be changed to evaluate different scenarios of carrying out the operation, a scaled human manikin and any other required 3D models of objects (e.g., steel plates, equipment, worktable) can be added to the point cloud environment, as shown in Figure 5. This addition has many analysis advantages such as evaluating ergonomic attributes such as clearance, fit, and visibility, as well as advantages for visualization such as facilitating the implementation of the required changes in the actual jobsite, communication of the proposed improvements, and worker training. To leverage these advantages, the human model can also include motion data of the worker inside the 3D environment. This is achieved by either using existing recorded motion capture data using motion sensors (e.g., Microsoft Kinect) or creating the motions inside the visualization environment (e.g., 3ds Max). Details of creating the motion data and performing automated ergonomic analysis on it can be found in Golabchi et al. (2015a).

Figure 5: 3D representation of workstation.

As the next step, the required inputs of the analysis must be obtained from the 3D representation. This is achieved by using measurements from the 3D model for quantitative attributes (e.g., distances) as well as by observing the model for descriptive features (e.g., body motion). Figure 6 shows some of the required inputs for the analysis and how they can be obtained from the 3D virtual representation of the workplace. As an example, the action distance value in Figure 6 can be simply obtained by selecting the start and end positions of the worker while carrying out the activity.

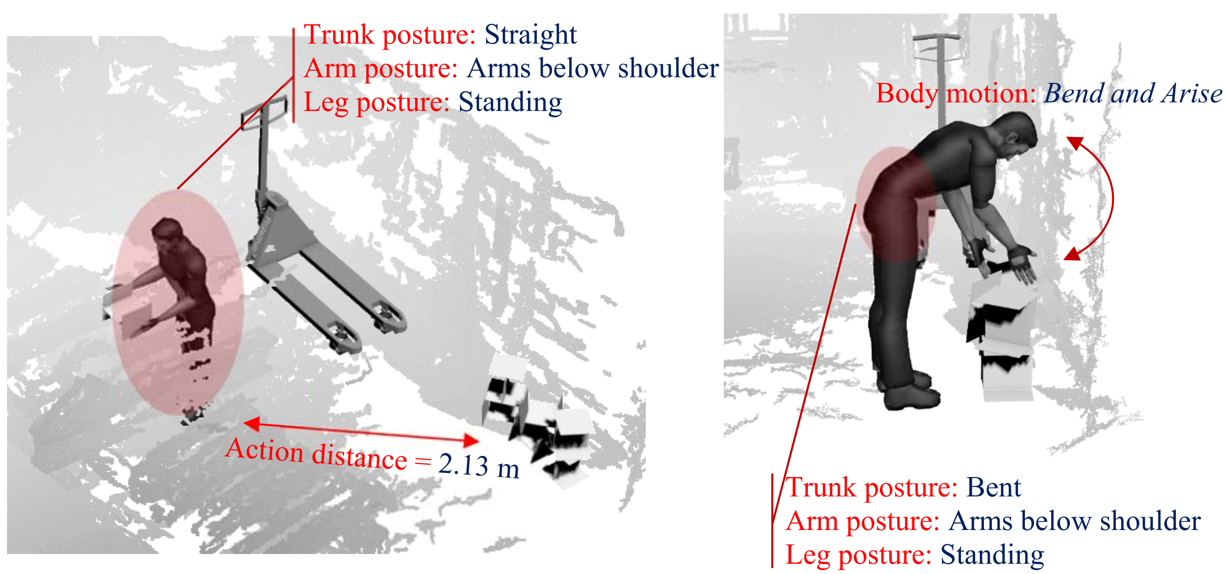


Figure 6: Extracting required inputs from virtual model.

Figure 7 shows all the required inputs for the efficiency and safety analysis, along with the various options that can be selected in the user interface designed for obtaining the inputs. After selecting the appropriate inputs, the simulation engine will run the MOST and OWAS analysis as described above.

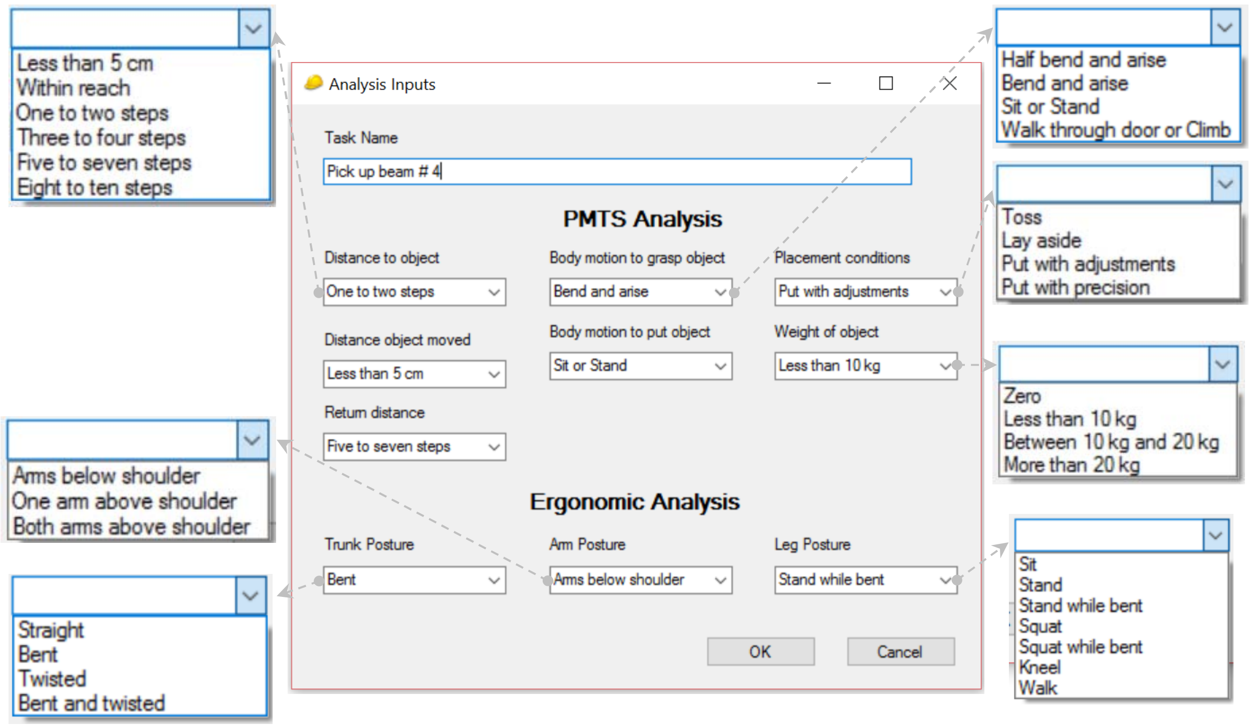


Figure 7: Inputs of MOST and OWAS analysis.

After running the efficiency and safety analysis, the results are used to evaluate the design of the operation and implement any required changes. In the case of the steel plate handling task, a potential modification can include arranging the steel plates on a worktable instead of the floor so that the worker does not have to bend and pick up the plates. This modification can be easily modeled in the 3D environment and used to evaluate the impact of the adjustment on the analysis as well as for other visualization purposes (e.g., communication, decision-making, training). The difference between the outputs of the two designs for one instance of carrying the steel beams to the worktable is shown in Table 2.

Table 2. Comparison of the existing and modified workplace.

	Workplace design	Duration (from efficiency analysis)	MOST code	Ergonomic risk (from safety analysis)	Intervention
Existing		9.00 sec	$A_6B_6G_3A_6B_0$ P_3A_1	Possible damage to the musculoskeletal system	Corrective action is required
Modified		6.84 sec	$A_6B_0G_3A_6B_0$ P_3A_1	Normal motion, without harmful effects on the musculoskeletal system	No action required

As shown in Table 2, the proposed modification not only improves the productivity of the operation, but it also eliminates a potential safety risk. The only modification to the workplace is providing a temporary table for stacking the steel beam sections, as opposed to placing them on the floor, so that the worker does not need to bend to pick up the beams. Based on the conditions of the workplace and the possible limitations, production planners can experiment with different designs and automatically compare them in terms of both efficiency and safety. Only one modification to the workplace is evaluated here for demonstration purposes and due to the simplicity of the operation. However, other potential adjustments to workplaces in general can include changing the location of material, tools, and equipment, modifying the type of equipment used, adjusting the height of the worktable, and adding workers to the crew. It should be noted that although Table 2 shows the result of the analysis for only one instance of a manual task, the proposed approach is typically used to model an entire cycle of manual operations, in order to capture the impact of repetition on the level of biomechanical exposure of different body joints. The novelty of the proposed approach, compared to similar analyses currently practiced in the construction industry, is not only in integrating PMTS analysis into simulation modeling, but also linking it to the visualization of the workplace. Using the virtual model reduces the time and effort required to carry out the analysis in addition to simplifying it, and also improves its accuracy and reliability. It can also be highly useful for implementation of the design by facilitating managerial decision-making, design communication, training, and etc.

4 CONCLUSION

This study has proposed an integrated simulation approach to analyzing the efficiency and ergonomic safety of manual operations that links predetermined motion time systems and ergonomic assessment to the 3D model of the workplace. Using photographs from an ordinary camera, the point cloud model of an existing working environment is developed and used to obtain the required inputs for the analysis. The results of implementing the approach in order to model a manual construction activity indicate its effectiveness in facilitating the analysis process by reducing the time and effort required to gather the analysis inputs, as well as eliminating the need for extensive knowledge and training regarding the details of the PMTS and ergonomic analysis. The approach can be used to visualize and reliably evaluate different scenarios of manual operations and select the most efficient one in terms of both productivity and ergonomics. The combination of DES and PMTS along with available ergonomic assessment methods is proven to be effective, as they complement one another by incorporating the various factors contributing to worker performance and safety.

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