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Adopting Lean Thinking in Virtual Reality-based Personalized Operation Training Using Value Stream Mapping

Abstract

Lean thinking has been proven effective in helping practitioners identify and eliminate wastes during engineering operations. However, systematic instructional mechanisms and training protocols based on individual trainee's performance are insufficient in existing training to define value-added activities for further productivity improvement in a training environment. This study aims to investigate how value stream mapping (VSM), as a lean tool, can be applied to help improve operation training performances through an immersive virtual reality (VR)-based personalized training program. A before–after experiment based on a virtual scaffolding erection scenario is established to simulate the training process. The training performance resulting from the VSM-based VR approach is compared with conventional VR training. Comparative results indicate that the waste time and errors reduce significantly. Compared with the conventional method, the overall productivity improvement of the erection process using VSM-based VR training is 12%. This demonstrates that integrating lean thinking into the operation training process can be a more effective approach for VR-based personalized operation training, provided that appropriate instructions are implemented.

Keywords: Lean; Value Stream Mapping, Virtual Reality, Personalized Training; Productivity

1. Introduction

Lean principles have been successfully adopted in the architecture, engineering, & construction (AEC) fields to increase profitability and productivity [1, 2]. Lean techniques and tools, such as value stream mapping (VSM), 5S, and just-in-time (JIT) offer new methods for identifying customer values and eliminate non-value-added activities [3]. Heravi and Firoozi [4] used VSM, which is a lean technique to systematically describe and investigate the production processes and further help identify wastes that can be removed from the process, in prefabricated construction. And they discovered that VSM is effective for time reduction and cost saving. In addition, workplace productivities in construction industries can be improved using 5S, especially in working areas [5, 6]. Ezema et al. [7] reported that JIT provided better work motivation and operation in manufacturing plants. Anderson and Kovach [1] demonstrated that lean methods could help reveal the underlying links of activities in each phase of maintenance projects to identify value-adding activities and waste. Construction industry training, if integrated with the lean method, can help employees learn how to eliminate waste effectively and achieve efficiency in construction operations.

Lean training aims to educate employees regarding operational processes more effectively, which is key to lean manufacturing. For example, Deros et al. [8] reported that the understanding level of trainees improved significantly when a lean training course is provided. Therefore, it is believed that the lean approach can be adapted accordingly for employees to implement process improvements more effectively. In addition, VSM, a lean tool, has been typically used in the education sector. Ahmad et al. [9] demonstrated that the integration of VSM into a project-based engineering curriculum can not only help students learn lean theorems, but also enable them to use VSM for problem solving.

Although lean training can be beneficial, most AEC training courses are conventionally conducted in classrooms, using examples and video clips from previous construction projects. Lean training through videos can assist trainees in visualizing construction tasks and activities; however, trainees cannot interact with the video environment. In recent years, researchers have adopted VR-related technology via building information modeling (BIM) [10, 11], game technologies [12, 13], and smart devices [14] to improve construction training performance. The advantages of adopting VR technologies in training compared with other means include enriched intractability, intuitive replicate of the reality, cost-saving, and safety guarantees [10, 15]. Li et al. [13] indicated that the VR-based training can help the trainees simulate safety hazards under the virtual work environment. This study demonstrates the weaknesses of the trainees who even have already passed the traditional field training processes and a VR-based training can further improve the understanding of safety hazards. Although these studies have proven that VR is effective for students or trainees, it is noteworthy that these VR training programs adopted traditional one-size-fits-all training methods that rarely consider the diversity of learning needs among individual trainees. According to Jeelani et al. [16], better training performances can be personalized owing to the knowledge gaps and learning needs of individuals. Jeelani et al. [17] stated that a more effective personalized training experience for construction workers can be provided through a virtual training environment.

Given the current gaps identified above, this study aims to investigate how VSM, as a lean tool, can be applied to help improve operation training performances through an immersive VR-based personalized training program. The specific objectives of this study are as follows: 1) to develop an immersive VR-based personalized training system to enhance training productivity for onsite workers; 2) to design and implement a systematic VSM-embedded training protocol to enhance training performance by adopting VSM; 3) to evaluate the overall performance of the training system.

This paper is organized as follows. Section 2 primarily discusses previous studies conducted in the areas of lean for education, VSM, and virtual and personalized training. Section 3 describes the proposed training protocol in this study. Section 4 presents the experimental process for evaluating the performance of the training system. Section 5 presents the results and discussions, followed by the conclusions and details on future studies being presented in Section 6.

2. Literature Review

2.1 The lean concept

The lean philosophy originated from the Toyota Production System [18], which maximizes value and reduces waste. Lean implementation in the manufacturing industry typically focuses on productivity improvement by reducing wastes and delivering the maximum value to customers. Wastes in the manufacturing industry are generally categorized into eight categories: overproduction, waiting, transportation, overprocessing, motion, inventory, defects, and unused talent [19]. Lean education is the adaption of lean thinking to identify and solve educational problems and improve learning and teaching activities. Antony et al. [20] translated eight wastes of lean manufacturing to the education sector, as shown in Table 1. Lean implementation in education can reduce cost and educational cycle time, as well as increase the satisfaction level for students, overall learning process [21], student academic experiences, and productivity [22]. In addition, engineers with lean knowledge are crucial to the development of modern lean enterprises, where employers are increasingly expecting the necessary engineering knowledge and competency levels. Lean education adopted in engineering processes may provide leading-edge approaches to content and competency mastery for workplace preparation [23].

Table 1. Waste translation from manufacturing to the education sector

Waste categories	Definition in the manufacturing sector	Explanation in the education sector	Explanation in the construction sector
Overproduction	Waste from making more products than customers demand	Course content or additional knowledge exceeds the requirement for the current learning process [24]	Construction task is completed faster than scheduled or before it is required in the process [25]
Waiting	Time spent on idling for the next process step to occur	Knowledge acquired by students must be retained until the following subject in the learning process [26]	Typically occurs when a worker is ready, but the materials required for work have not been delivered, or the previous task has not been completed [27]
Transportation	Transportation waste is the unnecessary movement of products and materials that do not create value	Movement of knowledge from one subject to another, which must be retaught, and the movement of materials related to the curriculum [24]	Materials, equipment, or workers are moved from one job site to another before they are required [28]
Overprocessing	Waste owing to more work than	Excessive inappropriate teaching and learning	Overprocessed construction activities that

	that required by the customer	processes for students [29]	have no value to the customer [30]
Motion	Waste time and effort related to unnecessary movements by people, machine, or equipment	Movement from one subject to another that is lacking the coherent streaming of curriculum, or the misunderstanding of the previous subject [26]	Unnecessary movements by workers to accomplish their work, which do not add value to the customer [31]
Inventory	Waste resulting from excess unprocessed products and materials	Knowledge must be retained for the future subject, which tends to be forgotten or becomes obsolete [24]	Materials stored on the construction site that are not required immediately [32]
Defects	Waste from a product or service fails to satisfy customer expectations	Shallow learning and failing to understand the related subject matter [29]	Defects in construction are incorrect work requiring rework or repair [33]
Unused talent	Waste owing to failing to utilize human talents, skills, and knowledge	Failing to recognize the ideas and suggestions of teachers and students for improvement [26]	Workers who have extensive experiences or skills are not matched to the right jobs on construction sites [34]

As shown in Table 1, the lean concept has been successfully used by construction companies to reduce project costs and waste on construction sites [1, 35]. Over 40 lean techniques and tools have been adopted in lean construction [36]. According to the study by M. Bajjou et al. [37], the most typically adopted lean tools for the construction industry include 5S, (JIT), poka-yoke, and VSM. Furthermore, a few of these lean tools have been used in the education sector. The current research gap can be discovered accordingly. Although the implementations have been proven useful in eliminating waste and improving productivity, studies focusing on how the related lean tools will contribute to construction training and education are limited [38, 39]. In addition, applying lean concepts in construction operations is still new, demonstrating strong research needs in this area [21].

Table 2. Definitions of related lean tools and applications in education

Lean Tools	Descriptions
5S	5S represents sort, simplify, sweep, standardize, and self-discipline, which refers to the effective management of production factors, such as personnel, machinery, and materials in construction sites [40]

Just-in-time (JIT)	JIT is a methodology for reducing waste in production, in which products are manufactured based on need, time of need, and the amount needed [36]
Poka-yoke	Poka-yoke, a Japanese term, is a mechanism to help operators avoid errors [41]
Value stream mapping (VSM)	VSM is a lean management method for visually analyzing and improving workflow circulation [37]

2.2 VSM for Engineering Education and Training

Among all available lean tools for engineering education and training, VSM has proven effective for process improvement. It can provide a better understanding of value-adding and non-value-adding activities from materials and information flows and deliver a product that satisfies customer requirements. Engineering and technology curriculum with VSM can be taught in classes to achieve learning objectives [42]. Lobaugh [43] used VSM to analyze the information flow of manufacturing processes in engineering fields for waste elimination. Steinlicht et al. [44] used VSM to map the educational process of a manufacturing engineering curriculum. The results showed that the course can be improved to better satisfy learning outcomes regarding the understanding of manufacturing processes and related technical information and skills. However, there are limited studies investigating the direct implementation of VSM in construction-related operation training for productivity improvement. It is expected to address the productivity issues of the related training practices through identifying operation wastes and eliminating these wastes.

2.3 Virtual Construction Personalized Training

Virtual training has been widely adopted in construction operations because it can improve the training outcomes and create a good opportunity for trainees to practice before they perform actual construction work. As an example, Li et al. [45] developed a multiuser virtual safety training system for a virtual tower crane operation process. The results showed that training performance improved significantly compared with the traditional training approach. In addition, the use of VR technologies in engineering design based on personalized learning has been demonstrated by Adas et al. [46]. This virtual learning environment can provide students with step-by-step instructions for interactions to achieve training objectives. Jeelani et al. [17] developed an immersive VR-based safety training environment that provided customized training elements for construction workers. It was demonstrated to be effective compared with the traditional “one-size-fits-all” method for knowledge and skill improvement. The summarized research effort can be seen in Table 3. The current research gap for VR in training is also identified. The previous VR-personalized training scenarios were preset and lacked unified measurements to recognize individual training performances. The instructions delivered by the trainer were based on their own knowledge and experience. A systematic judgment approach for providing sufficient guidance based on trainee performance is lacking. To improve training performance in operation productivity, VSM may be integrated into the processes of personalized training. Nevertheless, research regarding the integration of VSM in such a training scenario is non-existent, to the best knowledge of the authors.

Table 3. Summary of previous studies in VR operation training

Research	Description	Finding
Li et al. [45]	A multiuser virtual safety training system was developed for a virtual tower crane operation process	The results showed that the VR training performance improved significantly compared with the traditional training approach
Adas et al. [46]	The use of VR technologies in engineering design based on personalized learning was demonstrated	This virtual learning environment can provide students with step-by-step instructions for interactions to achieve training objectives
Cheng and Teizer [47]	A framework that involved real-time data collection and visualization for construction worker was developed	The operation information can be tracked and visualized for construction workers to improve their situational awareness
Le et al. [48]	A framework was proposed for construction site training based on mobile VR	Using mobile VR training would improve construction site safety
Jeelani et al. [17]	An immersive VR-based safety training environment that provided customized training elements for construction workers was developed	It was demonstrated to be effective compared with the traditional "one-size-fits-all" method for knowledge and skill improvement

3. Training Protocol Design

3.1 Overview of the Proposed Training Protocol

The research approach of this study is to propose a new VR personalized training protocol for integrating lean concepts in training guidance, and validating its usefulness through a user experiment by comparing it with the conventional VR training. As shown in Fig. 1, trainees usually go through a task briefing and lecturing session to know the details of the operational tasks. Then they will be immersing themselves in the VR environment and performing exercises to implement what they learned before. The performance will be recorded and further used by the trainers to give trainees feedbacks to address their specific weaknesses during the exercises. Afterward, trainees start to conduct exercise by referring back to the guidance and attempt to improve performance. This is a basic process for conventional VR training. The proposed training approach further introduce VSM as a tool to assist the achievement of three objectives: 1) performance analysis and waste identification on trainees' exercise results; 2) performance profiling based on performance analysis and waste identification for trainers to provide personalized coaching; and 3) productivity estimation for identifying trainees' potential improvement.

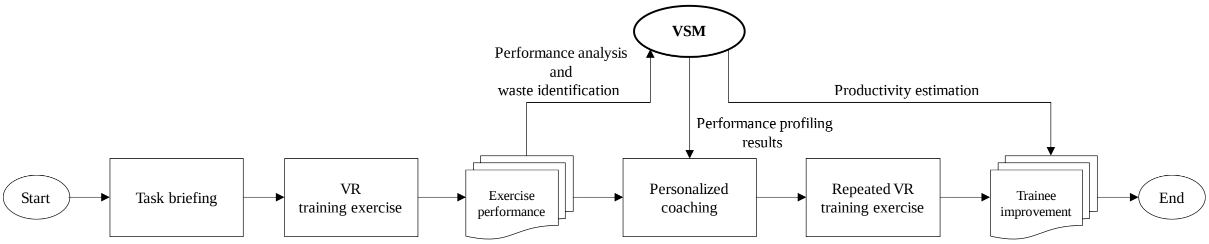

Figure 1: The proposed VSM-based VR personalized training process

In this study, the training task was set to be a scaffolding erection mission, which is typically performed prior to inspections under turnaround maintenance (TAM) in plant scenarios. The liquefied natural gas industry uses TAM to increase the reliability of plant facilities. In TAM, plants must be shut down periodically for inspections and repairs to maximize production capacity and ensure the reliable and safe operations of all equipment. A few weeks of TAM may incur a year's maintenance expense in terms of the direct cost of TAM and lost production [50]. Hence, temporary scaffolding works must be performed to address the special needs of repairing production equipment as well as schedule and process controls efficiently. Additionally, the related training process must be performed effectively.

VSM-based personalized VR training is proposed herein and compared with conventional personalized VR training, based on a virtual scaffolding erection scenario in a before-after experiment. The architecture of the comparative training protocols is shown in Fig. 2. The proposed training framework comprises three modules. First, a general scaffolding erection procedure is delivered to all trainees by lecturers. Subsequently, the trainees must familiarize themselves with the VR-based equipment under training scenarios and exercise scaffolding erection in the virtual environment individually. Next, the first round of exercises for trainees to complete the virtual scaffolding tasks is performed. Their performances during the operational processes are recorded, including the value-added time, number of errors, and lead time. The trainee performance baseline is hence identified (see Section 3.3 for more details). Subsequently, all trainees are randomly categorized into two groups. The first group focuses on conventional personalized guidance that provides instructions based on observations and trainee performances through the exercises. The second group is coached to provide instructions through VSM-based personalized guidance. The detailed procedure of the guiding process is detailed in Section 3.4. Subsequently, all trainees must reproduce the scaffolding erection operation under the same scenario. As discussed in Section 3.5, the performance of the second-round exercise for each trainee is assessed using the same indicators. Finally, the training productivity is estimated for further performance comparison.

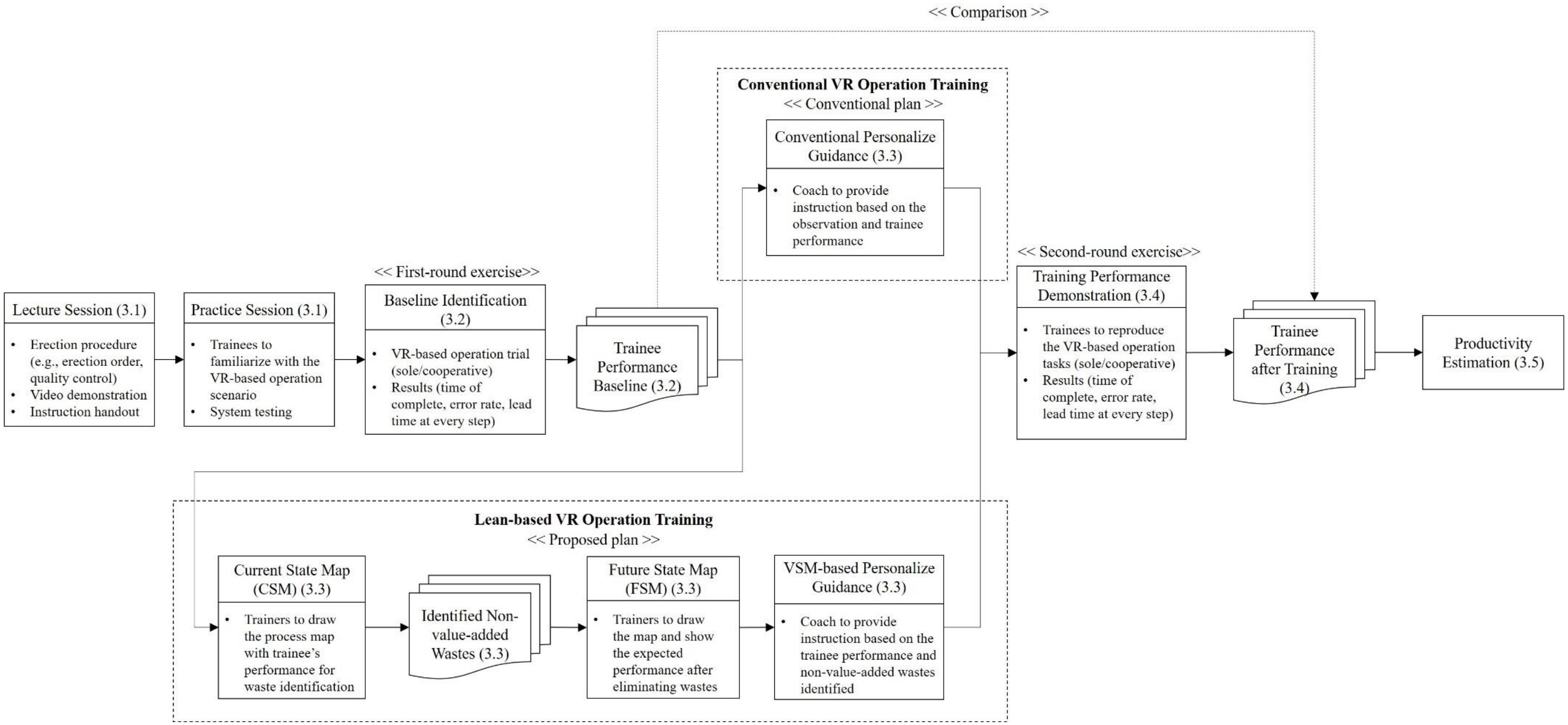

Figure 2: Architecture of training protocols under a before–after training scenario

3.2 Lecture and Practice Session

During the lecture, trainers introduce the general guide of scaffolding work to all trainees, including the scaffolding erection procedure shown in Fig. 3. Moreover, the policy for safe scaffolding erection and use has been established [49, 50]. The lecture kits include instructional handouts and video demonstrations. A two-story scaffolding erection task for plant tank inspection was selected as an example from the lecture materials in this study. In such a scaffolding erection, step one involves the appropriate preparation for scaffolding operators to define the work area and verify the availability of scaffolding components. Steps two to five comprise standard procedures for scaffolding foundation erection. Steps six to thirteen describe the process of the ground-floor scaffolding erection. The following steps until step 20 pertain to the first-floor scaffolding erection. As most of the steps were repetitive, the process was simplified into seven steps from the scaffolding erection process and adopted for the training experiments. The detailed steps of the process are shown in Fig. 4. It should be noted that steps two to six are related to the essential production process, while other steps are non-essential (e.g., safety precaution or hazard avoidance). Therefore, only steps two to six were considered in calculating the trainees' productivity performance in the virtual training environment. After the lecture session was performed, the trainees could familiarize themselves with the related VR equipment and scaffolding erection scenario through a practice session.

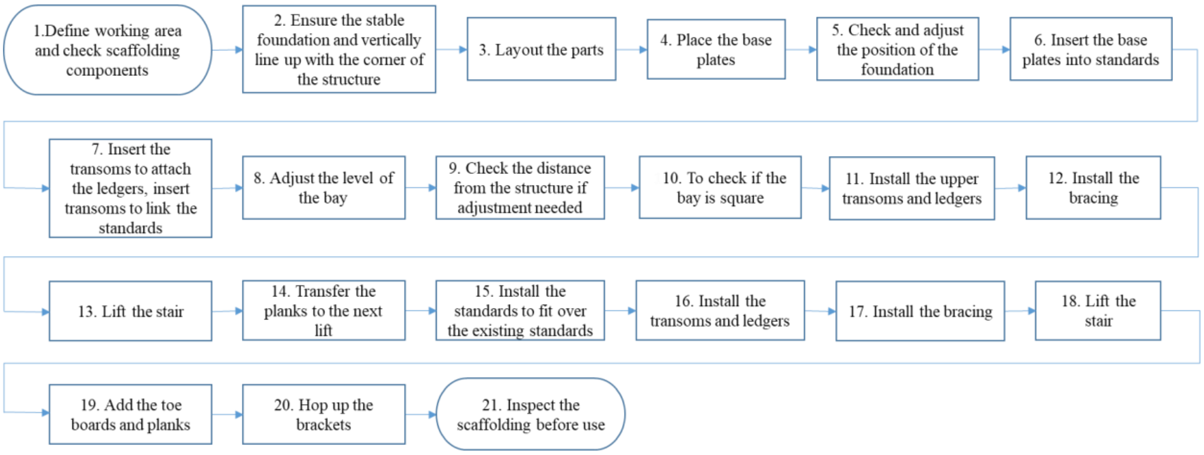

Figure 3: Scaffolding erection process

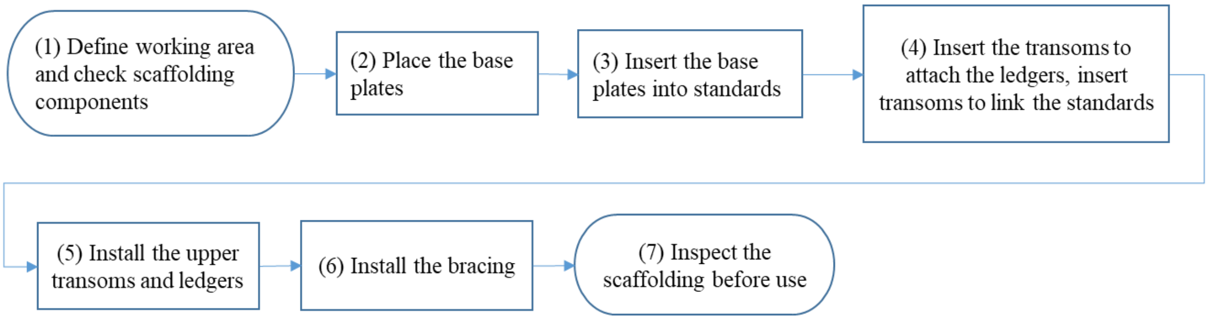

Figure 4: Steps selected for VR training experiments

3.3 Training Exercise for Baseline

To evaluate the potential benefits through the adoption of personalized training with or without VSM, a baseline of the trainees' performance must be established. As the first round of the official virtual operation exercise, each trainee participates in the virtual training scenario to perform the scaffolding operation based on what they have learned from the lecture. The Value-Added Time (VAT), number of errors, Cycle Time (CT), and waste categories in each step were recorded; the Lead Time (LT) and Processing Time (PT) of the scaffolding processes were calculated for further productivity evaluation. The PT is the duration between the start and finish time of the entire scaffolding erection process. The VAT is the processing time when the value-adding activities are performing during the scaffolding erection. VAT is the part of processing time, excluding Waste Time (WT) and non-value-adding time in the experiments. And it can be measured through excluding wastes and no-value-but-necessary behaviors during the operation, including picking up the wrong scaffolding components, carrying scaffolding components to be in position, assembling adjustment, unnecessary traveling, idling, and performing rework. The details are given in Table 4.

Table 4: Indicators of baseline identification

Indicators	Description
Lead time (LT)	LT is the time consumed from the beginning to the end of the scaffolding (specifically, steps 2 to 6 in Fig. 4) [51]
Processing time (PT)	PT is the time consumed for scaffolding erection (specifically, steps 1 to 7 in Fig. 4) [52]
Value-added time (VAT)	VAT is the processing time associated with value-adding activities (e.g., actual installation work) during the scaffolding erection [53]
Cycle time (CT)	Frequency of scaffolding erection completion by every step [54]
Number of errors	During the operation of steps 2–6 (in Fig. 4), the incorrect construction of each scaffolding component is recorded as one error (e.g., components misplaced with different dimensional requirements)
Waste time (WT)	WT is the time consumed by the trainee to perform the non-value-adding activity (as mentioned in the waste category)
Waste category	A: Taking wrong scaffolding components B: Unnecessary traveling C: Thinking (idling) D: Rework

3.4 Guiding Session through Conventional Method and VSM

After baseline identification, all the trainees were randomly categorized into two groups: Group 1 and 2. The feedback of the scaffolding erection process was provided to each group by the trainers. The outcomes of the training baselines enable the trainers to assess the performances of the trainees based on their training tasks or processes [55]. According to Hattie and Timperley [56], four levels of feedback exist: the task, processing, regulatory, and self-levels. Feedback at the processing level is beneficial to help trainees reject erroneous hypotheses and improve an individual’s training performance.

Hence, the video-assisted feedback method [57] was used as the conventional guiding approach for each trainee in the first group (Group 1). In addition, the trainers provided instructions based on their observation of the trainees’ performance, including waste categorization during the operation.

Unlike gathering the observational data to provide guidance for Group 1, VSM was used as a personalized guidance tool in Group 2. According to Rother and Shook [51], VSM can improve the process flow through four steps. The first step is to select the product family, which is the virtual scaffolding components to be erected in this study. The second step is to construct a current state map (CSM) for waste identification in the value stream of the erection process and describe waste in detail. It is the map that the trainers can use to guide the trainees systematically to identify potential productivity issues from the trainees’ performance. For instance, each step of the scaffolding erection process was drawn on the map as a chain connected by blocks. The trainee’s performance (e.g., VAT, LT, error, WT) at each step was listed on each block for trainers to identify if there are any significant wastes on a specific step of the erection process. The third step is to construct a future state map (FSM) based on waste elimination suggested by the trainers to set up an ideal goal for the individual trainee to follow. The final step is to achieve the future state, which is, in the study, to guide the trainees based on CSM/FSM evaluation results and allow them to perform a post-exercise to assess whether the identified wastes can be prevented. The trainers provide instructions and suggestions based on a CSM that allow the trainees to visualize the sources of waste at each scaffolding step. Furthermore, the FSM shows the proposed changes in the scaffolding operation for each trainee in Group 2 for further improvement.

3.5 Post-exercise and Improvement Evaluation

After Groups 1 and 2 have been trained through the conventional personalized and VSM-based personalized guidance, respectively, all the trainees reproduced the VR-based scaffolding erection process. These two groups were compared to demonstrate the benefits and differences between lean-based VR training and traditional training. LT, PT, VAT, and the number of errors during scaffolding erection were assessed for process improvement. Furthermore, training productivity was measured. In this study, the productivity index was considered in all the activities performed from steps two to six in Fig. 4, in which the trainees had to operate scaffolding components and place them at the correct positions.

4. Before–After Training Experiment

To evaluate the performance of the designed training protocol, the before–after training experiment was conducted. The participants of Group 1 used traditional personalized training (video and lecture), whereas those in Group 2 used VSM-based personalized training to learn how to perform the scaffolding erection. To evaluate the training efficiency, the VAT (min), WT (min), errors, and PT (min) to accomplish the training tasks were used to evaluate the trainees in the two groups.

4.1 VR-based Scaffolding Erection Scenario and Participants

The design of the virtual scaffolding erection scenario is shown in Fig. 5. The virtual scenario was modeled using Unity3D, which is a game engine to create a virtual interactive environment. The virtual models, including the scaffolding components, foundations, and tanks to be inspected, were created using Autodesk Revit 2018, a BIM software; they were exported in the FBX format and imported to this virtual environment. The components of the scaffolding included 22 base plates, 22 standards, 62 transoms and ledgers, and 10 diagonal bracings, as shown in Fig. 5.

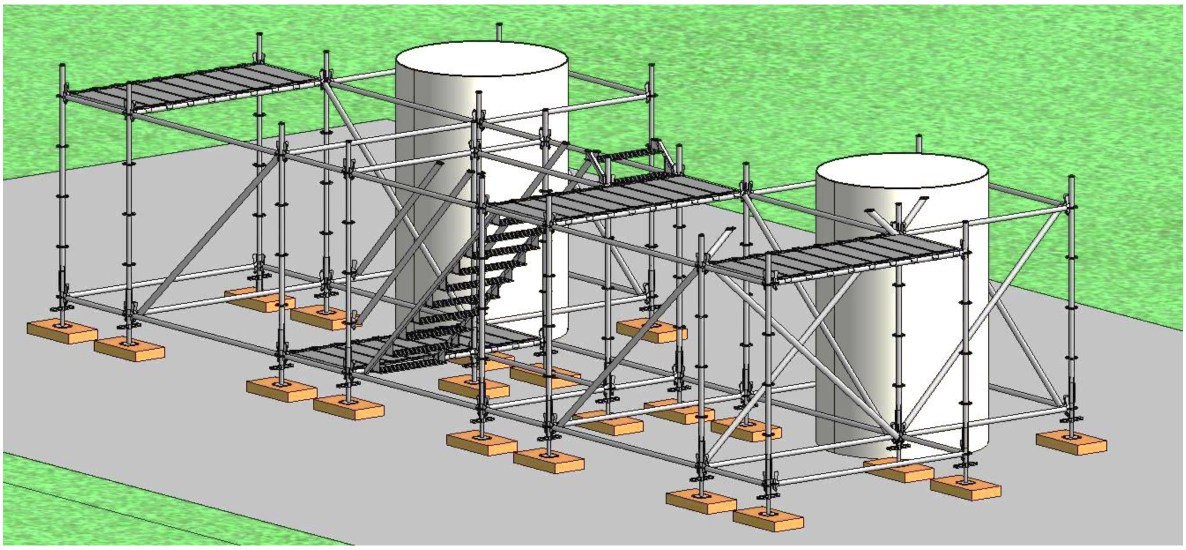

Figure 5: Overview of the virtual scaffolding erection scenario

The participants in the experiment were 32 male undergraduate students who have no experience related to VR operation and scaffolding construction. They were from the School of Engineering and Technology at Southwest University, China. The average age of them was 21.3 years old, with a range of 20 to 22. The 32 students were randomly assigned to Groups 1 and 2. Each group comprised of 16 students. As shown in Fig. 6, all the trainees had to perform the scaffolding erection in the virtual environment using the VR equipment. The hardware includes a head-mounted display device, computer monitor, and game controller. Detailed information regarding the environmental setting of the experiment is shown in Fig. 7. Detailed configurations of the hardware are provided in Table 5. In the experiment, the student participants wore the VR headset and held the controller to perform simulated erection activities in the virtual scenario. A facilitator, a researcher who is also the trainer, monitored the behaviors of the participants by viewing the monitor that displayed the projected information of the virtual scenario. The facilitator was responsible for recording the performances of the participants, identifying errors, and conceiving effective instructions for personalized guidance.

Table 5. Detailed configurations of the VR hardware equipment

Hardware	Purpose	Description
Headset	Provide immersive virtual scaffolding erection scenario to the participants	The HTC VIVE headset used has a refresh rate of 90 Hz, 110° field of view, and display resolution of 1080 × 1200
Wireless controller	Grasp and release scaffolding components in the installation positions in the virtual scaffolding erection scenario	The HTC VIVE wireless controller includes a trackpad, grip buttons, and dual-stage trigger
Monitor (with PC)	Project participants' views and actions in the virtual scaffolding erection scenario to the trainer and perform videotaping	Dell S2340L 23-Inch screen LED-Lit monitor was used and synchronized with the headset

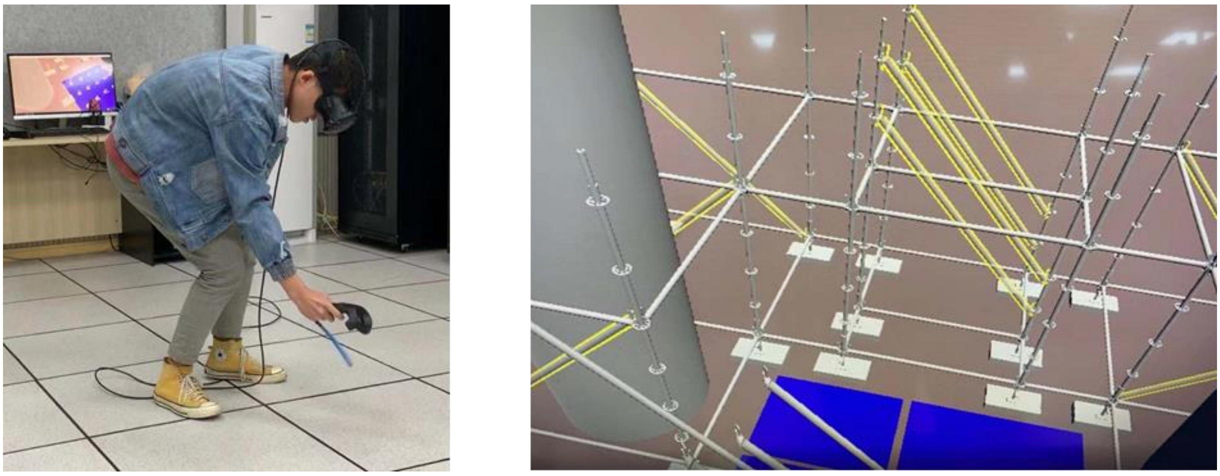

Figure 6. Example of simulated scaffolding erection operation in the virtual environment

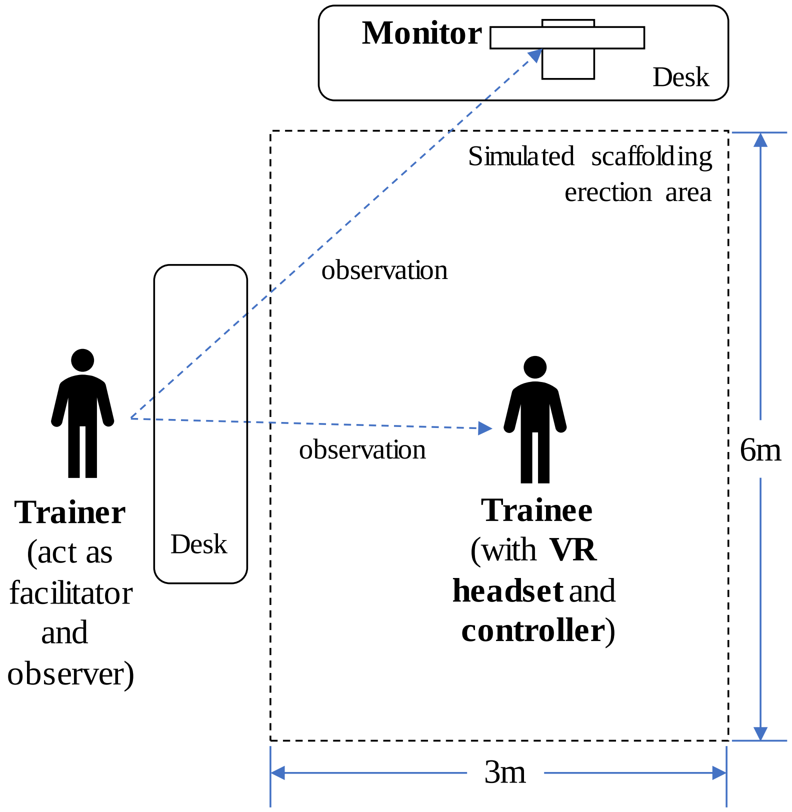

Figure 7. Environmental settings of the simulated scaffolding erection scenario

4.2 Evaluation of the Training Performance

The training performance of the participants was evaluated from four aspects: time, error, productivity, and satisfaction. For time recording, it was recorded in seconds and then converted to minutes, rounding to one or three decimal places. The detailed evaluations include comparing the significance between the different performance of the two groups in terms of time and error, assessing corresponding productivities, and evaluating trainees' confidence in undertaking the individual training through a questionnaire survey.

A t-test for identifying statistical significance was adopted to validate whether a significant difference occurred between the performances of the two groups. According to Johnson [58], if $p < 0.05$, then their performances are significantly different; if $p \geqslant 0.05$, they are not. In addition, to adequately compare the training performances of the two groups, baselines were identified to ensure that the participants (trainees) in the two groups have similar prior knowledge and abilities in performing the simulated operations without personalized instructions. To perform the adjustments, the performance of the first round exercise (baseline) under each indicator before training in Group 1 was used, and the others were adjusted to the corresponding baselines. The adjustments were computed through a standardization method. It was assumed that the performance before the training exhibited an identical statistical distribution, which was characterized by the mean and standard deviation in the standardization method. In the adjustment approach, $X_{1,0}$ and $X_{1,u}$ were the performances before and after training for Group 1, respectively, and $X_{2,0}$ and $X_{2,v}$ were those for Group 2, respectively. The performances before training in Group 2 was adjusted as follows:

$$X'_{2,0} = g(X_{2,0})sd(X_{1,0}) + mean(X_{1,0}), \tag{1}$$

where $X'_{2,0}$ is the adjusted performance for $X_{2,0}$, $g()$ is the standardization function, $sd()$ is the standard deviation, and $mean()$ is the mean value. The standardization function is calculated as follows:

$$g(X_{2,0}) = \frac{X_{2,0} - mean(X_{2,0})}{sd(X_{2,0})} \tag{2}$$

Consequently, the adjusted performance $X'_{2,0}$ has the identical statistical distribution parameters, mean, and standard deviation values, which ensures the same baseline and comparativeness of the two groups through observations. Correspondingly, the performance after training in Group 2 was adjusted as follows:

$$X'_{2,v} = h(X_{2,v})sd(X_{1,0}) + mean(X_{1,0}), \tag{3}$$

where $X'_{2,v}$ is the adjusted performance for $X_{2,v}$, and $h()$ is a modified standardization function for $X_{2,v}$ according to the baseline of $X_{2,0}$, which is calculated as follows:

$$h(X_{2,v}) = \frac{X_{2,v} - mean(X_{2,0})}{sd(X_{2,0})} \tag{4}$$

By adopting the adjustment equations (1) – (4), performance in terms of time and error in Group 2 are normalized to those of Group 1 with identical statistical distributions for further comparisons.

To further evaluate the overall training productivity between the two training approaches, the productivity index [59] was calculated as follows:

$$P = (Q_a - Q_b)/(T_f - T_s) \tag{5}$$

where Q_a denotes the number of processing activities, Q_b is the number of non-value-adding activities, T_f and T_s are the finish and start time of operation.

To evaluate the trainees' confidence qualitatively, questionnaire surveys were adopted. Five questions were posed as follows: (1) the task and instruction were easy to understand and helped in learning-related information; (2) I can easily and quickly identify the waste when reproducing the training tasks; (3) I can effectively complete the designated training tasks; (4) the training approach was helpful and effective; (5) overall, I was satisfied with the training process. The participants were requested to assign a rating from 0 to 10 (0: completely disagree; 10: complete agree) to each question. A paired-sample test was used to compare the effectiveness of the lean-based VR personalized training with the traditional training, according to the qualitative results obtained from the trainees.

5. Experimental Results

The experimental results, including the before–after exercise performance, CSM, FSM, and productivity indices, were gathered. The average duration of the lecture session was about 40 mins, and that of the practice time for each trainee to familiarize himself with the VR environment was about 30 mins. About 20 mins were spent on personalized guiding sessions in the case of the VSM-based VR training process.

5.1 Performance in terms of Time and Error

As for the first group (Group 1) related to the traditional training guidance, the before–after training performance is as shown in Table 6. The average VAT before and after the training was 17.4 and 16.1 mins, respectively; the WT was 11.9 mins and 9.3 mins, respectively; the error was 33.8 and 29.8, respectively; and the PT was 29.2 and 25.4 mins on average, respectively.

Table 6: Before–after training performance of Group 1

Group 1								
Trainee No.	VAT before training (min)	VAT after training (min)	WT before training (min)	WT after training (min)	Error count before training (times)	Error count after training (times)	PT before training (min)	PT after training (min)
1	19.7	18.5	16.4	10.1	35	28	36.1	28.6
2	15	16.1	9.4	6.2	30	27	24.4	22.3
3	15.5	17.1	14	10.3	35	31	29.5	27.4
4	14.8	14.7	7.7	8.1	27	28	22.5	23.3
5	21.5	19.6	14.5	12.1	47	39	36	31.7
6	13.8	13.9	7.7	8.4	22	26	21.5	22.3
7	20.2	18.5	12.2	9.7	47	39	32.4	28.2
8	19.9	18.1	15.2	10.3	44	31	35.1	28.4
9	11.4	11.6	9.4	9.7	31	31	20.8	21.5
10	17.5	16.3	11.0	9.0	33	30	29.0	24.8
11	18.1	13.8	15.2	5.7	31	20	33.3	19.5
12	15.7	14.6	8.3	8.8	22	23	24	23.4
13	17	15.4	9.5	7	22	20	26.5	22.4
14	20.6	17.6	16.9	14.5	52	44	37.5	31.1
15	17.9	14.3	8.8	7.2	22	20	24.7	21.5
16	20	18.2	13.9	12.5	40	40	33.9	29.7
Average	17.4	16.1	11.9	9.3	33.8	29.8	29.2	25.4

The second group (Group 2) underwent a VSM-based personalized training, and the before–after training performance of Group 2 is shown in Table 7. Similar to the trend of Group 1, the average VAT before and after the training was 16.8 and 15.2 mins, respectively; the WT was 12.4 and 8.0 mins, respectively; the error was 37.2 and 24.0, respectively; and the PT was 29.3 and 23.2 mins on average, respectively.

Table 7: Before–after training performance of Group 2

Group 2								
Trainee No.	VAT before training (min)	VAT after training (min)	WT before training (min)	WT after training (min)	Error count before training (times)	Error count after training (times)	PT before training (min)	PT after training (min)
1	18	15.3	12.2	8.8	36	21	30.2	24.1
2	13.9	13.8	7.6	4.4	27	12	21.5	18.2
3	18.5	16.6	14.2	8.7	44	28	32.7	25.3
4	21	18.2	14	8.2	48	28	35.1	26.4
5	15.7	14.6	11.5	7.1	40	23	27.2	21.7
6	18.5	15.8	12.8	8.6	34	23	32.3	24.4
7	16.6	15.3	13.8	8.7	34	26	30.4	24
8	18	15.8	8.8	6.1	27	20	26.8	21.9
9	15.6	15.2	12.0	8.1	36	24	28.7	22.9
10	13.6	12.3	8.2	6.2	23	21	21.8	18.7
11	17.4	15.4	12.2	7.2	37	19	29.6	23.6
12	18.3	14.3	15.1	9	48	24	33.4	22.3
13	15.8	15.7	16	10.2	44	35	32.1	25.9
14	17.1	15.5	12.8	7.5	35	22	29.9	23
15	15.9	16.1	13.8	9.6	42	30	29.7	26.2
16	14.7	13.7	13.3	9.9	39	28	28	23.6
Average	16.8	15.2	12.4	8.0	37.2	24.0	29.3	23.2

To identify the waste during the scaffolding erection process for each trainee in Group 2, a CSM was first constructed based on the trainee's performance baseline and videotaping to determine the appropriate strategy for improvement. Fig. 8 shows an example of a CSM based on the performance of a trainee. Once the CSM was shown to the trainee, the trainee and trainer discussed the metrics that require improvement. The waste types of each activity that contributed the most were listed, such as the waste categories, WT, number of errors, and PT. The trainer first determined the maximum errors and WT in each activity. For example, as shown in the figure, most of the errors occurred in Activity 2 (10 times), but only five errors in Activity 3 caused more time waste. Finally, the trainer discussed with the trainee to determine possible improvement approaches to transform a CSM to an FSM, i.e., to improve the scaffolding erection performance. Subsequently, the ideal FSM was created by the trainer and trainee. As shown in Fig. 9, all sources of waste were expected to be eliminated adequately for the trainee's reference.

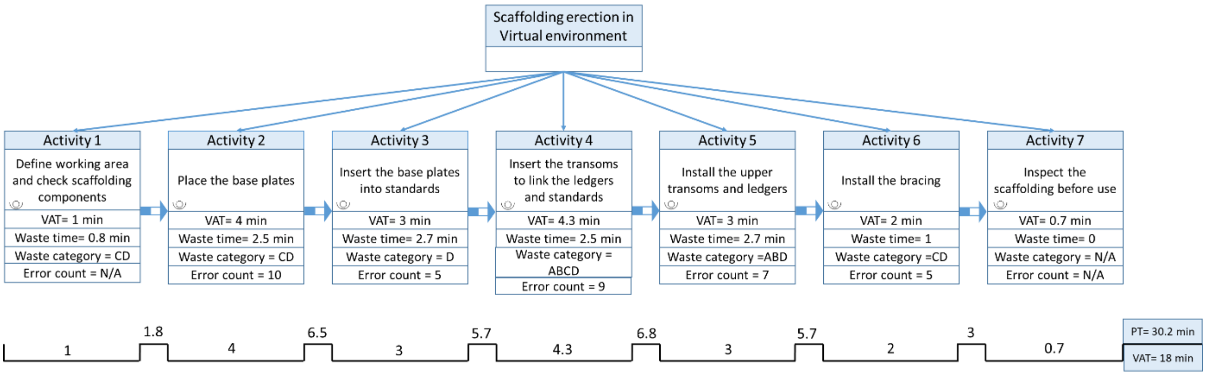

Figure 8. Example of CSM based on a trainee's performance in Group 2

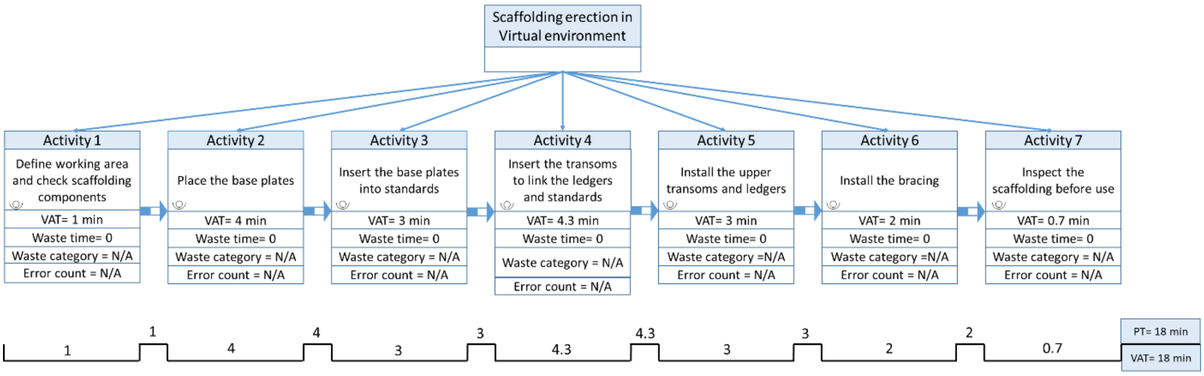

Figure 9. Example of ideal FSM based on a trainee's performance in Group 2

In terms of baseline adjustment, the result of the t-test before the training is as shown in Table 8. The p-values of the VAT, WT, error count, and PT were 0.562, 0.660, 0.309, and 0.901, respectively. The p-values for all indicators were much higher than 0.05, implying that the two groups of participants (Group 1 and normalized Group 2) did not differ significantly before the training.

Table 8: Performance comparison before the personalized training using t-test

Indicator	Mean of Group 1	Mean of Group 2	t value	p value
VAT (min)	17.407	16.867	0.588	0.562
WT (min)	11.940	12.420	-0.445	0.660
Error Count (times)	33.800	37.200	-1.038	0.309
PT (min)	29.880	29.380	0.255	0.801

As for the performance improvement after the personalized training approaches, the t-test is further conducted, as shown in Table 9. The VSM-based personalized training is significantly better than the conventional personalized training in terms of WT elimination ($t = -4.066; p = 4.72\text{E}-04 < 0.05$), error reduction ($t = -5.957; p = 3.68\text{E}-06 < 0.05$), and PT improvement ($t = -3.945; p = 5.08\text{E}-04 < 0.05$). However, the VAT ($t = -1.899, p = 6.79\text{E}-02 > 0.05$) between the two groups was not significantly different after the training. All the comparative results related to t-tests have been validated through Cohen's d benchmark [60]. The value of Cohen's d for 95% confidence interval was tested on a scale of medium to large size effect, which is 0.71 for VAT, 1.54 for waste time, 2.25 for errors, and 1.49 for processing time.

Table 9. Performance improvement comparison after personalized training using t-test

Indicator	Improvement Mean for Group 1	Improvement Mean for Group 2	*t* value	*p* value
VAT (min)	1.273	2.443	-1.899	6.79E-02
WT (min)	2.567	5.993	-4.066	4.72E-04
Error Count (times)	4.000	17.863	-5.957	3.68E-06
PT (min)	4.460	10.264	-3.945	5.08E-04

In terms of the comparative summary between the conventional and VSM-based personalized training, the average performances of each indicator are presented. Fig. 10 shows the training effectiveness between conventional and VSM-based personalized training after baseline adjustment. The effectiveness is presented from three aspects, including the statistical summaries shown in boxplots, mean value variations of the two groups, and the mean values of confidence after the training.

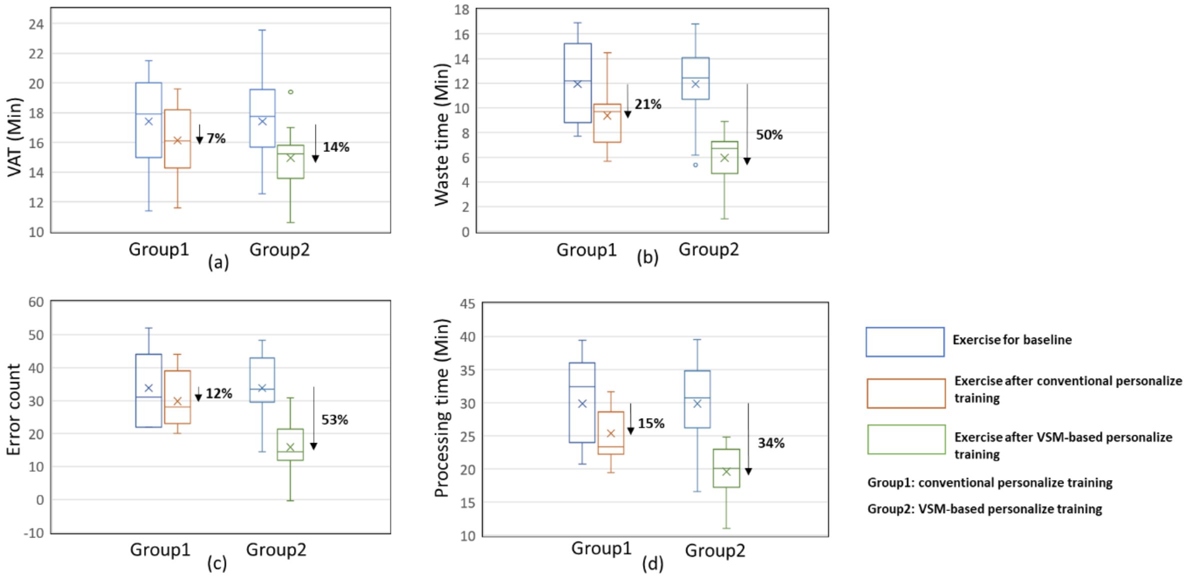

Figure 10. Comparison of conventional and VSM-based personalized training: (a) Value-added time; (b) Waste time; (c) Error count; and (d) Processing time

The training effects quantified by the VAT, as shown in Fig. 10 (a), indicate that the VAT can be reduced critically by the personalized training approach. It was assumed that the effect of familiarity was reduced or eliminated through the practice session. Furthermore, there are two different groups of participants who perform the exercises by using different training approaches individually, instead of using the approaches sequentially. So, the effect of the familiarity issue can also be minimized through the normalizations of the two groups' results. In general, the mean VAT of the baseline exercise was 17.41 mins, and the standard deviation was 2.95 mins. After the conventional VR training exercise (Group 1), the mean VAT was 16.13 mins, a 7% improvement of the VAT compared with the baseline. On the other hand, due to the accurate training guidance and more confidence in operations with the CSM and FSM, a 14% improvement of the VAT, with the mean VAT of 14.96 mins, was observed.

The training effects quantified by the WT are shown in Fig. 10 (b); the mean WT of the baseline was 11.94 mins, and the standard deviation was 3.36 mins. After the conventional VR training, the mean WT was 9.37 mins, which was reduced by approximately 21%, when compared with the baseline in Group 1. In addition, by using the VSM-based personalized training, the mean WT was now 5.95 mins, which is a 50% reduction. In other words, using VSM-based personalized training can reduce unnecessary travel, rework, and errors more effectively when compared with conventional personalized training.

The training effects quantified by the error count are shown in Fig. 10 (c), showing a significant difference between the two groups. The mean error count of the baseline is 33.8 times, and the standard deviation is 10.2 times. After the conventional VR training, the mean errors in Group 1 were 29.8 times, which was a 12% decrease. The mean errors of Group 2 were 15.9 times (approximately a 50% decrease), which was a more significant reduction compared with that of Group 1 after the VSM-based personalized training was introduced. As the error details were provided to the individuals for each step of the scaffolding erection task through VSM, a significant reduction was expected.

The training effects quantified by the PT are shown in Fig. 10 (d); the mean PT of the baseline was 29.8 mins, and the standard deviation was 6.5 mins. After the conventional VR training exercise, the mean PT was reduced by 15% to 25.4 mins compared with the baseline. In the VSM-based personalized training group, the mean PT was 19.6 mins, which was reduced by approximately 34% due to the overall error times and WT reduction.

5.2 Training productivity evaluation

An example of the productivity estimation can be seen in Table 10. It is based on one trainee's performance after he obtained the personalized training. As can be seen from the table, the total number of scaffolding erection activities is 166, the number of non-value-adding activities is 28, the start timestamp is 0.9, and the finish timestamp is 28.6. The productivity index can be thus estimated to be 3.30.

Table 10: An example of trainee's productivity profile

Exercise after the personalized training – Trainee 1								
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Total
Number of activities	N/A	Place 22 base plates	Insert 22 base plates into standards	Insert 31 bottom transoms	Installation of 31 top transoms	Installation of 10 bracings	N/A	166
VAT (min)	0.9	2.5	3.5	5	3.8	1.8	1	18.5
WT (min)	0	1.7	1.6	3.8	2	1	0	10.1
Waste category	N/A	D	D	ABD	ABCD	CD	C	N/A
Error count (times)	N/A	3	5	11	6	3	N/A	28
PT (min)	0.9	4.2	5.1	8.8	5.8	2.8	1	28.6
Productivity								3.30

Waste category: A: Taking wrong scaffolding components; B: Unnecessary traveling; C: Thinking; D: Rework

Tables 11 and 12 show the productivity indexes of the two groups after the training. Because the training efficiency improved in both groups, the average productivity of Group 2 was higher than that of Group 1. The productivity improved by approximately 12%, from 3.76 to 4.24. This was primarily attributable to a significant error and WT reduction in Group 2.

Table 11. Productivity index of Group 1 after the conventional personalized training

No.	Q_a	Q_b	T_s(min)	T_f(min)	P
1	116	28	0.9	27.6	3.30
2	116	27	1	21.7	4.30
3	116	31	0.7	26.7	3.27
4	116	28	1.5	22.8	4.13
5	116	39	0.4	30.6	2.55
6	116	26	1	21.5	4.39
7	116	39	0.8	27.4	2.89
8	116	31	1.3	27.6	3.23
9	116	31	1.4	20.6	4.43
10	116	30	1	23.8	3.77
11	116	20	0.5	19	5.19
12	116	23	0.8	22.5	4.29
13	116	20	0.7	21.6	4.59
14	116	44	1	30.3	2.46
15	116	20	0.8	20.8	4.80
16	116	40	1.2	29.2	2.71
					Average = 3.76

Table 12. Productivity index of Group 2 after the VSM-based personalized training

No.	Q_a	Q_b	T_s(min)	T_f(min)	P
1	116	21	0.9	23.4	4.22
2	116	12	0.6	17.7	6.08
3	116	28	1	24.5	3.74
4	116	28	1.2	25.4	3.64
5	116	23	0.6	20.9	4.58
6	116	23	0.5	23.8	3.99
7	116	26	1	23	4.09
8	116	20	0.7	21.3	4.66
9	116	24	1	21.9	4.40
10	116	21	0.7	17.9	5.52
11	116	19	1.2	24.8	4.11
12	116	24	0.8	21.6	4.42
13	116	35	1	27.3	3.08
14	116	22	0.7	24.5	3.95
15	116	30	1.2	25.5	3.54
16	116	28	1	24.1	3.81
					Average = 4.24

5.3 The trainees' confidence evaluation

All the trainees were instructed to complete the designed questionnaire, and the results are shown in Fig. 11. As shown, adopting the VSM-based personalized training over the conventional personalized training is advantageous in terms of waste identification (from 5.75 to 6.94), effectiveness (from 5.56 to 6.63), helpfulness (from 5.75 to 6.56), and satisfaction (from 5.81 to 6.81). However, the two groups did not differ much in terms of knowledge acquisition (from 6.06 to 6.31).

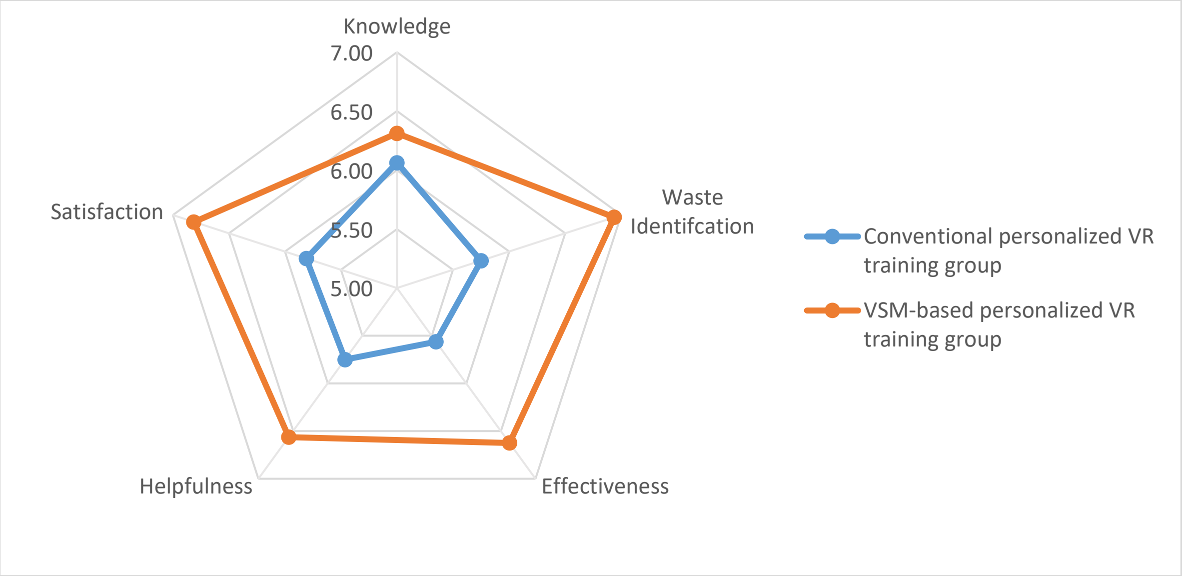

Figure 11. Comparison of mean values of training effects between the conventional and VSM-based personalized VR training groups

6. Discussion

Based on the experiment results and observations, some discussions are provided as follows:

- As can be seen from Table 8 to 12, the improvement of VR-based personalized operation training by VSM includes time reduction, error elimination, and productivity improvement. The average PT of the two groups was reduced after the individual training approaches, but VAT has not been improved significantly compared with other performance indicators of the two groups. This shows that there is no significant difference between the two personalized training approaches for trainees to learn what essential tasks (value-adding activities) are and how to complete the scaffolding operations. The advantages of the VSM-based personalized training from the conventional VR approach is that VSM helps the trainees systematically understand their wastes during the scaffolding erection processes through CSM, and further develop the strategy to eliminate them through FSM. This is also reflected in the results of time reduction, error elimination and productivity improvement.
- As all participants in the experiment did not have any prior lean knowledge and related scaffolding construction background, further benefits of adopting VSM in the operation training were identified. Graphically describing the operational process and involving

the trainees in the creation of the CSM and FSM could help them clearly identify wastes that could be eliminated during the training. The overall productivity (Table 11 and 12) through the VSM-based training improved from 3.77 to 4.23, approximately a 12% increase compared with the conventional approach. As shown in Fig. 10, the significant improvement after the training was based on the reduced numbers of errors (improved from 12% to 53%) and WT (improved from 21% to 50%). These were consistent with the characteristics of VSM used in the manufacturing and construction sectors [9, 43], which were efficient in identifying and removing/reducing wastes among value streams. As the VAT decreased by 7% and 14% in Groups 1 and 2, respectively, it was observed that after the VSM-based training, the trainees could not only identify the problems during operation but also could use an efficient strategy to manage wastes and errors for improvement. For instance, one participant claimed that "compared with a previous VR training I attended, in which the comments were always provided, I can identify the mistakes I made during each step of the operation more effectively in the current training, and I feel more confident in operating after receiving the instructional feedback." Judging by the similar responses from participants, VSM can be regarded as an effective tool that provides systematic information related to the training process and fills the gap between knowledge required by the trainee and the expected improvements after the training. A CSM can confirm both correct and incorrect activities in detail, and an FSM can indicate the directions pursuable by the trainees to achieve higher operational productivity.

- Even though the learning content did not increase by using the VSM-based approach, the CSM and FSM were constructed during the guidance sessions not only for the training improvements, but also to facilitate the spread of lean thinking to the participants. Furthermore, the participants gained the knowledge to use VSM for problem-solving. As shown in Fig. 11, the agreement levels for knowledge acquisition in terms of the scaffolding erection task did not change significantly. As stated by one of the participants: "I did not learn more about scaffolding erection through the VSM-based personalized training; however, this approach allowed me to learn about lean, which I was not aware of previously. Furthermore, it taught me to solve problems in a different approach."

- The design of the experiment and the VSM-based approach can be further improved by encapsulating a more sophisticated virtual scenario and more tools for process automation. Although the VSM-based personalized training achieved a better performance than the conventional approach, it was only proven in a simplified scaffolding erection scenario. As mentioned by one of the participants: "I can maintain high attention during the reproduction operations for the seven steps of the scaffolding process. However, if the operation process is more complicated, I may not be able to remember the steps and perform all improvements even if they are identified by the VSM-based approach." In reality, the scaffolding process involves more than seven steps, including safety precautions and ergonomic issues, which must be considered. Further arrangements to split the training sessions to avoid information overloading is necessary. Moreover, the CSM and FSM mapping processes in the future should be automatically generated and displayed in the virtual training scenario for reducing guidance time, as recommended by most of the participants.

- The observations of the experiment were aligned with educational and perceptional loading principles, in that, a trainee would learn more if the training materials and feedback information were condensed and systematic [61]. The struggles from trainees who were taught via the conventional approach could be caused by the personalized feedback information from the trainers, which was always diverged and sometimes more or less than required. According to LeMahieu et al. [62], trainers must understand how trainees perceive values and how the values can be transferred into the learning process. As shown from the results, VSM, as a lean tool for training, can easily help trainers to systematically identify aspects of the operational improvements that facilitate the learning of the entire scaffolding erection process. In addition, VSM processes can classify wastes and operational errors for individuals with organized thinking to the solutions, whereas the conventional approach relies significantly on the experience of the trainers and their communication skills.

7. Summary, Conclusion and Future Studies

In many studies, VSM has been used as a lean tool to reveal the wastes, inefficiencies, and non-value adding activities for productivity improvement in manufacturing and construction sectors [63, 64]. Given its benefits, the effectiveness of VSM in construction education and training, especially when integrated with other advanced technologies, such as VR, should be investigated. VR has proven to be effective in providing better understanding and visualization capabilities. Pedro et al., [14] argued that many studies on VR training focus on the isolated application of VR to address a specific training need, it is imperative to understand how to improve the training productivity individually. Studies [45, 46] have demonstrated that VR can help improve individual operation training performance, but these training platforms do not systematically provide effective instruction and feedback for individuals. Compared with prior studies, this study provides an example of how VSM, as one of the lean tools, can help VR personalized operation training to improve training productivity.

To determine the benefits of lean thinking in operation training, a VR scaffolding erection scenario, as an example, was conducted in this study to evaluate the training effectiveness between conventional and VSM-based VR personalized training. The former requires conventional training guidance, in which the trainers educate trainees directly through video recordings and observations. The latter implies a lean-based training approach, in which the trainee is trained systematically using VSM tools. From the results identified in the experiment, both approaches could effectively enhance the VR training performance. However, adopting VSM-based personalized guidance demonstrated better productivity improvement than adopting the conventional personalized guidance. Furthermore, participants in conventional training demonstrated significantly higher error and WT reduction. Hence, VSM-based personalized training was more efficient compared with the conventional VR training approach, which relied significantly on the experience of trainers. The overall training productivity improved by 12% compared with conventional training. This demonstrates that VSM, as a lean tool, is more effective in reducing waste during the teaching and learning processes and offers a good example of how lean thinking can facilitate VR operation training. The contribution of this study is that a systematic VSM-based VR personalized training protocol is developed to enrich the learning tools of operation training by integrating lean thinking into the training process. Compared with conventional training processes, VSM-based training can effectively improve training productivity, especially in waste identification and error reduction.

However, this study has certain limitations. All the test participants were civil engineering undergraduates aged 20 to 22, without any experience in VR operation, and all were males. The actual onsite workers may come from different countries and have different cultures, which could have a certain impact on the effectiveness of training. Differences of the participants in age and gender during the training could be further discussed, too. They can be verified in future studies. The process of scaffolding erection was simplified in the VR training scenario, in which only seven steps were designed, and only the essential procedures of the operation were considered. The sense of weight, safety precautions, and working posture were not evaluated in the VR training scenario. Moreover, the training scenario was only suitable for a single-person training process. In reality, the tasks may be completed by multiple workers with the potential of cooperation. Future studies will focus more on addressing the abovementioned limitations by further investigating the ergonomics and safety indicators and extending the scenario to a multiuser cooperative scenario, which can yield a more realistic operation simulation. Approaches to automatically generate CSMs and FSMs will be considered for future improvements.

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