**School of Design and the Built Environment**

# Developing a Virtual Reality- and Lean-based Training Platform for Productivity Improvement of Scaffolding Installation in Liquefied Natural Gas Industry

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**This thesis is presented for the Degree of**
**Doctor of Philosophy**
**of**
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## DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics (For projects involving human participants/tissue, etc) The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number # HRE2019-0051.

Signature:

Date: 25/07/20

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## ABSTRACT

The liquefied natural gas (LNG) industry uses Turnaround Maintenance (TAM) to improve the reliability of production equipment and ensure production capacity. TAM projects require onsite employees to obtain a higher level of understanding related to the technical specifications. TAM projects also require tremendous amounts of scaffolding to facilitate relevant industrial operation and maintenance. As such, the productivity of scaffolding operations in TAM has attracted much attention in recent years. In addition, health and safety issues have been recognised as a key contributor along with productivity improvement in the LNG industry. Training and education therefore plays an extremely important role in raising the level of understanding in TAM projects on reducing project variability and improving efficiency and health and safety.

Virtual Reality (VR) technologies have proven to be beneficial in the education and training of construction workers on construction activities. However, there are limited studies which focus on how VR can be incorporated into the training process of TAM projects. Given the complexity of TAM projects, traditional education and training on isolated processes may not be adequate to achieve efficiency. In addition, as the lean approach, which is a method to identify waste in production and construction by classifying all activities into value adding and non-value adding, is now commonly adopted in the LNG industry to identify waste and improve productivity, it is useful to investigate how the lean concept can be embedded into the VR-based education and training platform.

This research aims to develop an innovative framework that integrates lean and work postures so as to simultaneously improve productivity and health and safety, as well as developing a VR-based platform for effective education and training in TAM projects.

Firstly, to identify research gaps and problems, a comprehensive review on VR related research and application in construction engineering education and training (CEET) is conducted. From the review, VR-related technologies and their applications in CEET are identified, and the implementation areas of these technologies are investigated. In order to analyse lean implementation in the construction sector, a

bibliometric analysis is adopted to reveal the evolution of lean construction research since its inception.

Secondly, a case study approach is adopted to integrate lean and work posture analysis in a TAM site to investigate how lean should be adopted to increase productivity, as well as improving health and safety performance. The lean improvement is conducted through value stream mapping (VSM) and the work posture analysis is conducted through the Ovako Working Posture Analysis (OWAS) System method. A three-step optimisation strategy is then developed for achieving an optimised performance in waste reduction and work posture improvement. It is found that the implementation of VSM can help eliminate waste in the installation process, therefore eliminating potential health and safety risks. However, health and safety of onsite workers does not always improve as lean implementation intensifies. Site workers therefore need to be more systematically trained for an optimised lean implementation.

Thirdly, based on the case study, an immersive VR training platform is developed to investigate how VSM as a lean tool can be applied to help improve operation training performance through an immersive VR personalised training. The performance of the VSM-based VR training is compared with the conventional VR training. The results show that integrating lean thinking into the VR-based training environment can be a more effective approach by providing personalised operation training, provided that appropriate instructions are implemented.

Finally, to address the issue of limited collaboration from conventional VR training and investigate how effective collaboration can be integrated into a VR training environment to raise productivity in scaffolding installation, a collaborative VR training platform is developed where participants are able to communicate and collaborate. Six teamwork competencies are evaluated including adaptability, coordination, and decision-making, interpersonal, leadership, and communication. The results show that the collaborative VR training platform has better performance in the above six competency areas.

Theoretical and practical implications of this thesis are also provided for researchers and relevant stakeholders. In contradiction to previous studies, which rely on qualitative assessment to identify a positive correlation between lean and health and safety, this study reveals the distinct difference between lean attributes and health and safety attributes through a quantitative assessment and the approach is more readily to be implemented at the site level for simultaneous improvement in lean and health and safety. The practical contribution of this research is a systematic VSM-based VR training protocol and a collaborative training protocol by integrating lean thinking into training process for training productivity improvement, especially in waste identification and error reduction.

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| | |
|---|---|
| AR | Augmented Reality |
| BIM | Building Information Modelling |
| CAD | Computer-Aided Design |
| CEET | Construction Engineering Education and Training |
| CSM | Current State Map |
| CT | Cycle Time |
| DOFs | Degree-of-Freedoms |
| FSM | Future State Map |
| HMD | Head-Mounted Display |
| ICMLS | Interactive Construction Management Learning System |
| IoT | Internet of Things |
| JIT | Just in Time |
| LLR | Log-Likelihood Ratio Tests |
| LNG | Liquefied Natural |
| LPS | Last Planner System |
| LT | Lead Time |
| MI | Mutual Information Tests |
| MTM | Method-Time Measurement |
| OSHA | Occupational Safety and Health Administration |
| OWAS | Ovako Working Posture Analysis System |
| PT | Processing Time |
| TAM | Turnaround Maintenance |
| TF*IDF | Term Frequency*Inverse Document Frequency |
| TPM | Total Productive Maintenance |
| VAT | Value Added Time |
| VM | Visualisation Management |
| VR | Virtual Reality |
| VSM | Value Stream Mapping |
| WoS | Web of Science |
| WT | Waste Time |

# Chapter 1: Introduction

## 1.1 Background

The LNG industry uses Turnaround Maintenance (TAM) to increase plant facilities' reliability. The aim of TAM is to maximise production capacity and ensure reliable and safe operation of all equipment. Maintenance and upgrading of equipment is to improve production speed and efficiency. It is a periodic maintenance that the plants need to be shut down for inspections and repairs. Planning a TAM workflow must address the special needs of repairing production equipment. According to Ben-Daya et al. (2009), TAM projects have short duration and high intensity. A 4-5 weeks of TAM may cost the entire year's maintenance budget. TAM is also a costly affair in terms of lost production and labour costs. In reality, the duration of LNG turnaround projects always exceeds the scheduled time due to delays of maintenance activities (Liu et al., 2008; Shou et al., 2015). The LNG industry has spent much time on improving maintenance processes and gained much experience over last twenty years, but it is found that there are still many problems predominately caused by delays. Shutdown management aims to enhance TAM processes, by reducing the average delay time and increasing the work efficiency of workers during the shutdown period (Van den Heuvel, 2008).

Training is an organised activity for increasing the knowledge and skills of an employee for doing a specific job. The training programme can set up a suitable simulation environment to teach knowledge and practices and help trainee make better decisions and achieve effective problem solving (Mirehei et al., 2011). According to Nieto-Montenegro et al., (2008), a training programme needs to be based on appropriate education such as learning materials and practical training, which incorporates activities that support the development of skills that are relevant to real life situations in which the workers can put information into practice.

Due to the rapid changes in the technology of the LNG industry, providing sufficient training programmes to improve the daily activities of employees has played an important role in the entire LNG industry. According to a survey by Society of Petroleum Engineers (2012), most participants stated that proper training is crucial to the development of employees. In particular, about 60% of respondents stated that technical training is the most important training in LNG industry. Nowadays, it is also recognised that the employers should not only hire employees, but should provide facilities and schemes for their further training and education on maintenance engineering (Ben-Daya et al., 2009). Current training programmes on maintenance are often based on traditional methods, including on-the-job training and information-based training. Pennathur and Mital (2003) stated that training a workforce on-the-job can face possible damages due to the lack of experience. Also, practical training should not influence the ongoing work, which may be difficult to achieve in on-the-job training (Gadre et al., 2011). Ariga et al. (2013) found that it is difficult to measure the effect of a training session on productivity at the individual level. Similarly, Jenkins et al. (2011) pointed out that information-based training such as handbooks, lectures or procedures is difficult to equip decision-makers with appropriate stored-procedures to cope with various situations. New training schemes are necessary to help address these difficulties.

For building and construction projects, construction processes need to be completed on time and with good quality. The training of construction workers therefore mainly focuses on technical issues and safety awareness. Compared to construction processes, LNG plant operations, especially TAM processes, have the following characteristics that make the application of traditional construction training ineffective:

- TAM of LNG projects are expensive. A few weeks of TAM may cost the equivalent of a year's maintenance budget in terms of direct cost of TAM and lost production capacity (Duffuaa and Ben-Daya 2004). An appropriate training programme such as VR based training (Li et al., 2018) that can provide clear objectives and practices is important for TAM projects to meet the budget requirement and save the potential losses due to the cease of production.
- The whole LNG plant needs to be shut down for working on equipment. The shutdown requires a great many of maintenance personnel and time to carry out maintenance
- , and also defects could not be repaired during operation. Because of the distinct features of the maintenance work in TAM projects, on-site work conditions are usually not revealed until the TAM begins. Therefore, the scope of work involved in TAM has considerable variations and uncertainties (Lenahan, 1999; Levitt,

2004). Therefore, the employees need to be trained for reducing shutdown durations by eliminating unnecessary work and with proper scheduling. Otherwise, turnaround delay and cost overrun can happen.

- Compared with the construction process, human error is very common in maintenance operation (Ben-Daya et al., 2009). It can include distraction and forgetting important checks of permitted work procedure in order to save time. Some of human error could be so often that they become the accepted practice. Poor maintenance will increase the number of breakdown, which can increase the risk of equipment failure and personal accident (Ben-Daya et al., 2009). Hence, a better training of maintainers and operators is expected.

Lean maintenance has been successfully used in the turnaround industries to increase profitability and productivity (Anderson & Kovach, 2014; Mostafa et al., 2015). Lean techniques and tools, such as Value Stream Mapping (VSM), 5S, Just in Time (JIT) bring in a new way of being to help identify customer values and eliminate non-value added activities (Zhang & Chen, 2016). Heravi and Firoozi (2017) used VSM as a lean technique to investigate the production processes in prefabricated construction and found that VSM application is effective in time reduction and cost saving. In addition, workplace productivities in construction industries have been improved by using 5S, and it is more effective to conduct the working area (Bayo-Moriones et al., 2010). Ezema et al., (2016) showed that JIT provides better work motivation and operation in manufacturing plant. Anderson and Kovach (2014) demonstrated that lean method could help the project team to reveal the underlying links of activities in each phase of maintenance project in order to identify value adding activities and waste. A TAM training, which integrates the lean method will help employee learn how to effectively eliminate waste and achieve efficiency in maintenance operations. The successful TAM training will therefore help increase the up-time for production and reduce relevant maintenance costs.

The traditional approach of process improvement focuses on the equipment and value added processes. Such process improvement can help improve project uptime. However, it should be noted that the improvement is usually achieved in specific processes. The overall impact on the entire value stream is usually overlooked. For example, Kuhlang et al., (2011) developed the methods-time measurement (MTM) approach to reduce lead time and increase productivity. Wiyaratn and Watanapa (2010) developed the systematic layout planning to increase productivity in the plant. Instead of focusing on specific production or maintenance processes, the entire value stream of the process is mapped in lean (Thomas and Joseph 2006). In addition, the lean method motivates employees as employee involvement is considered as one of the most important values in the lean concept. De Treville and Antonakis (2006) pointed out that lean production job design may improve employees' intrinsic motivation. Lean training is to motivate the employees who are related to production directly. Motivated employees are often more flexible and can understand the process more effectively which is also a key element of lean manufacturing. For example, Deros et al. (2012) showed that trainees' level of understanding is improved significantly after they had lean training course. It is therefore believed that the lean approach can be usefully adopted for employees to better understand the knowledge and skills for process improvement.

According to Ker et al., (2003), trainers play an important part in a training session which could lead to different outcomes based on their profiles and their pedagogic level. Most of the TAM training courses (such as PetroKnowledge training course) are conducted in a classroom. Examples and video clips of past TAM projects are used to aid the learning and understanding of the TAM process. Although video learning could assist trainees in visualising TAM tasks and activities, trainees cannot interact with video environment. VR, as an effective tool, has proven to be effective on providing better understanding and visualisation capabilities. For example, in engineering education and training, students can perceive different spaces through a 3D object, rather than viewing traditional drawings. VR is a significant improvement on traditional 3D approaches which rely on the use a mouse or keyboard to interact with the computer-generated structural form. In the VR environment, the immediate results of interactive activities, such as pulling and grabbing, can be visualised in a real-time manner.

Virtual Reality (VR) technologies has been rapidly recognised in construction engineering education and training (CEET) programmes because they are believed to be effective in enhancing the quality of such programmes. There are many studies which have demonstrated the positive impact of VR in such adoptions (such as Chen et al., 2007; Dehlin et al., 2008; Goedert et al., 2011; Russell et al., 2013; Pedro et al., 2015). Goedert et al. (2011) developed a virtual interactive construction training platform which provided game-based safety training through the use of simulation and modelling. The advantages of using VR in training are related to its ability to enable trainees to interact with each other within virtual three dimensional (3D) environments. Intuitive senses about the learning subjects can also be developed by interacting with the objects, related messages and signals in the virtual environment. Different from the conventional education and training approaches, such as the utilizations of static pictures or two dimensional (2D) drawings, VR's visual representation allows more degree-of-freedoms (DOFs) to be integrated. In additional, VR technologies have been adopted for task-based training in heavy industries (Lucas & Thabet, 2008; Varela & Soares, 2015). Langley et al. (2016) established the virtual training system for assembly operations within the automotive industry. It shows that VR training is effective in avoiding error during the task when compared with conventional training processes. Hou et al. (2017) proposed a framework to improve the process of the complex procedural skills in oil and gas facilities. The results reveal that VR training system clearly promotes workforce productivity while bringing down rework.

## 1.2 Problem statement

Natural gas, as cleaner burning fuel, is becoming increasingly important in many countries and regions to accelerate economic growth. Australian Bureau of Statistics (2018) stated that LNG exports, which will reach nearly 63 million tonnes valued at $ 30.4 billion in 2018, are an ongoing source of strength for Australia's economy. In addition, Australia has almost $80 billion worth of LNG projects under construction (APPEA, 2017). In order to maximise production capacity and ensure reliable and safe operation of all equipment, the LNG industry needs periodic maintenance on site, during which the LNG plants need to be shut down for inspections and repairs. According to Ben-Daya et al. (2009), TAM projects have short duration and high intensity. A 4-5 weeks of TAM may cost the entire year's maintenance budget. TAM is also a costly affair in terms of lost production and labour costs. According to a survey by ManpowerGroup (2011), the workers in the Australian LNG industry are among the highest paid in the world, earning about $US 140,000 per year compared to a global average of $US 76,000. In reality, the duration of turnaround projects in LNG industry always exceeds the scheduled time due to delays of maintenance activities (Liu et al., 2008; Shou et al., 2015). According to Hansen (2016), two-thirds of turnaround maintenance projects exceed their budget and their schedule are delayed by more than thirty percent. Human error is a major contributor to delays and planned cost escalations during TAM work (Mhlanga et al., 2016).

The LNG industry has therefore spent much effort on improving maintenance processes and gained extensive experience over the last twenty years, but it is found that there are still many problems predominately caused by delays. Complex structures of LNG plants require ever-changing of scaffolding construction for maintenance purposes. Onsite erection and dismantling can negatively impact production activities (Moon et al., 2016). Scaffolding, as temporary structures, has a significant impact on construction operation and maintenance. The unique requirements of these temporary structures can often lead to delays caused by poor scaffolding planning and scheduling, time and spatial constraints, including unnecessary rework and long travelling between activities, which will directly affect the productivity of the plant (Moon et al., 2016). In addition, due to time-space conflicts and hazards, scaffolding activities are not always safe for onsite assembly workers (J. Kim et al., 2014). Shou et al. (2015) analysed the TAM project of a selected LNG refinery plant using work sampling study and found that scaffolding modifications for facility lift are key to meet project schedule and there is a clear indication for improvement in terms of the reduction of lead time.

Health and safety in construction operation is always a critical issue in the LNG industry (Forte & Ruf, 2017). Health and safety issues such as ergonomic analysis of the construction workers has been recognised as a key contributor for improving productivity in construction industries (Kyaw-Myint et al., 2015) According to Occupational Safety and Health Administration (OSHA 2005), about 2.3 million construction workers work on scaffolding regularly, and accidents related to scaffolding cause 4,500 injuries and $90 million in damage per year in US. Previous studies, which have adopted lean to improve TAM process, predominately use time and cost savings as performance indicators. For example, Kovach et al. (2014) demonstrated that lean method can help the project team reveal the underlying links of activities in each phase of maintenance project in order to identify value adding activities and waste. Kuhlang et al., (2011) developed the methods-time measurement (MTM) approach to reduce lead time and increase productivity. It is necessary to integrate health and safety considerations into the process so that a balanced improvement on productivity, as well as health and safety can be achieved.

Studies confirmed that VR training system can be used to create effective training activities for the LNG industry. VR training can also stimulate learning and promote trainee interaction. However, there are limited studies which focus on how VR can be incorporated into the training process of TAM projects by integrating with the lean concept. Many studies focus on the isolated application of VR to address a specific training need (Pedro et al., 2015), without considering how to improve the workforce training productivity.

## 1.3 Scope and aim/objective

In order to tackle the problems stated above, this research aims to develop an innovative framework that integrates lean and work postures so as to simultaneously improve productivity and health and safety, as well as developing a VR-based platform for effective education and training for scaffolding installation in TAM projects.

To achieve the research aim, the following four objectives are established:

**Objective 1:** To identify VR-related research and application in construction engineering education and training (CEET), as well as lean implementation in construction sector.

A comprehensive literature review of the current VR-related research and application in CEET and lean implementation in construction are conducted in order to identify the gap between the current VR training programmes and reveal the evolution of lean research in construction.

**Objective 2:** To integrate the lean construction and work postures in scaffolding installation in TAM projects to simultaneously achieve improved workflow and optimised risk index.

Based on the review, this research investigates how the lean concept and work posture analysis can be integrated into scaffolding installation in TAM projects. The lean improvement is conducted through VSM and the work posture analysis is conducted through the Ovako Working Posture Analysis System (OWAS) method.

**Objective 3:** To develop an innovative VR- and lean-based platform for the education and training in scaffolding erection in TAM projects.

An innovative VR- and lean-based platform for the education and training of TAM employees will be developed. The benefits of the platform, compared with traditional VR training, will be validated through a case study.

**Objective 4:** To systematically evaluate the effectiveness of the platform for training improvement.

A systematic evaluation of the effectiveness of the platform in improving TAM training will be conducted. The evaluation aims to investigate whether there is a significantly improvement in training productivity when using the platform.

## 1.4 Significance

LNG companies have committed to training their workforces due to the significantly negative impact of productivity in the oil and gas industry. Many companies are therefore re-evaluating and systematically improving the method of skill training development. **In this research, there are three significant contributions shown as below**:

**(1) Integrating lean and health and safety knowledge**

Previous studies that reveal lean implementation has positive impact on health and safety for onsite worker rely on qualitative assessment. This research adopts a quantitative approach to demonstrate the relationship between lean and health and safety performance. At the theoretical level, such knowledge provides empirical evidence for the construction industry to understand the attributes of lean and health and safety knowledge and how the attributes of these two important concepts interact with each other.

**(2) Improve the labour productivity for LNG industry**

According to the APPEA (2013), the cost of delivering liquefied natural gas to Japan from Australia is 30% higher than delivering from Canada. The rising cost of LNG production in Australia put tremendous pressure on the survival of Australian LNG projects. Increasing productivity in Australian LNG projects is therefore extremely important and significant. This research will help the trainees learn how to effectively eliminate waste in TAM project. It will improve TAM operational process with minimum constraints or waste and maximum value by meeting customer demands.

**(3) Improve the effectiveness of employee training in LNG industry**

A growing number of companies in LNG industry are piloting studies to improve labour productivity through the use of innovative 3D virtual planning, simulation and visualisation technologies. Such virtual training is important because LNG plant is complex and potentially dangerous. VR system is also easy to perform the TAM operations scenarios without workers being on the actual LNG plant. Employees can access the plant layout, walking and evacuation routes, and understand specific TAM operations and procedures in virtual environment. In addition, LNG plant facilities are often in remote areas and difficult and expensive to access. By using VR technology, companies can leverage software to recreate the exact facilities, enabling maintenance teams to simulate the trainings unlimitedly based on needs. In addition, the cost of the VR-based training is much cheaper than sending them to remote facilities directly. Utilizing VR-based training to incorporate lean maintenance method can enable the visualisation of plant operations, providing a useful platform for skill development, especially for entry-level trainees to learn complex operation.

## 1.5 Thesis structure

This thesis has nine chapters, as shown in Figure 1-1.

**Chapter 1** describes the introduction, research problem, aim and objectives of this thesis, as well as the thesis structure.

**Chapter 2** summarises the literature on lean in construction sector, also discusses the definitions of related lean tools and applications in education, and virtual training in construction engineering education and training,

**Chapter 3** outlines the research methodology, including research method for reviewing VR application in CEET and lean construction research; research method for integration of lean and work postures analysis; research method for training protocol design; and research method for VR- and lean- based operation training.

**Chapter 4** develops optimal scaffolding erection through the integration of lean and work posture analysis, which consists of two main sections: lean improvement through VSM and work posture analysis through OWAS method; a three step optimisation strategy is developed.

**Chapter 5** is to design the training protocol for VR based personalised operation training using VSM, including the architecture of training protocols and before-after training experiment, also to evaluate the training performance, including performance in terms of time and error, training productivity evaluation, and trainees' confidence evaluation.

**Chapter 6** is to evaluate the effect of VR collaborative training on teamwork skills.

**Chapter 7** concludes the thesis and explains the contributions and implications. Suggestions related to future research are also provided

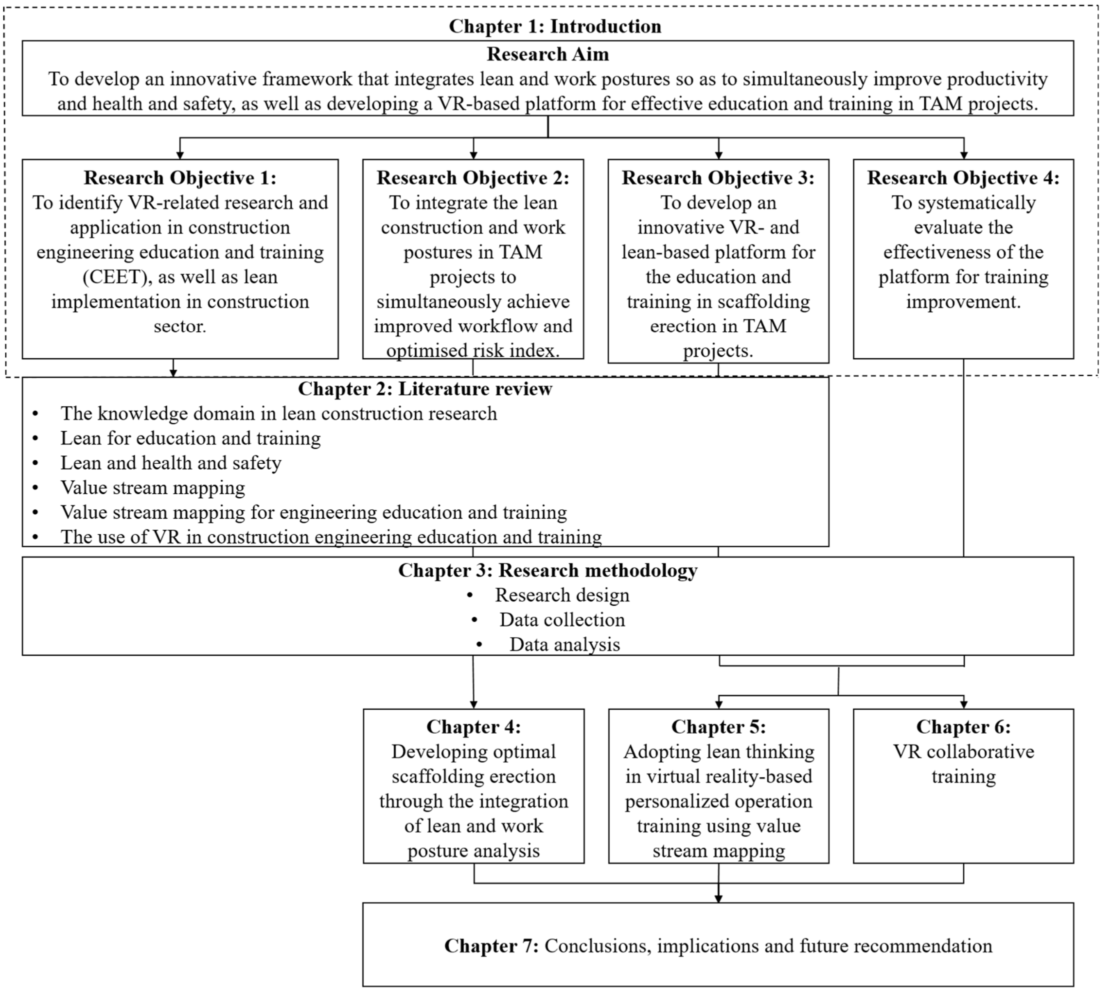


Figure 1-1: Structure of the thesis

# Chapter 2: Literature review

This chapter is to review and summarise lean and VR in construction training and education. The chapter is organised as follow. Section 2.1 presents the knowledge domain in lean construction. Sections 2.2 and 2.3 reviews lean concept for education and training and previous studies which have investigated lean and health and safety. Section 2.4 discusses VSM in construction and education sector. Section 2.5 reviews the use of VR in construction engineering education and training. Section 2.6 summarises this chapter.

## 2.1 The knowledge domain in lean construction

Since its inception in the 1990s, lean construction has been recognized as a systematic approach, which can help customer with waste identification and elimination (Hines et al., 2004). The concept originates from the automobile industry and is initially known as the Toyota Production System (Ohno, 1988). This system can help identify seven categories of waste, including overproduction, defects, inventory, process, transportation, waiting and motion. Gradually, other sources of waste, such as underutilization of employees, have also been identified to broaden the concept of waste in lean. Krafcik (1988) is the first study that adopts lean as a term to represent the Toyota Production System. Gradually, lean construction is commonly adopted to represent the complicated socio-technical system with the key objective of waste elimination (Shah and Ward, 2007).

As an advanced management approach for process improvement, lean principle has been widely utilised in manufacturing sector to handle complex production systems through increased flexibility, lower costs and improvement in product quality (Romano et al., 2009; Stump & Badurdeen, 2012; Zhou et al., 2016). Successful lean implementation in manufacturing industry have resulted in a strong push for introducing lean to construction. In the construction area, the first publication is dated from 1992. Koskela (1992) revealed the new lean philosophy to construction to explore and adopt the lean construction concepts and tools.

Lean construction has been widely adopted to address workflow issues in construction project since the early 1990s (Arashpour & Arashpour, 2015; Brodetskaia et al., 2012). Due to the rapid development in lean technique, such as internet of things

(Dave et al., 2016), the contribution of Building Information Modelling (BIM) (Gurevich & Sacks, 2014) to lean implementation, last planner system (LPS) (Kim & Ballard, 2010), simulation (AbouRizk et al., 2016), and location-based management (Olivieri et al., 2018), lean construction has been gradually adopted as a key approach of research design to address several important topics in project management, such as production planning and control, sustainability, and supply chain management (Hamzeh et al., 2012; Segerstedt & Olofsson, 2010; Song & Liang, 2011).

A quantity of lean construction review articles have been published in the last ten years. Some of these review articles have traced lean theory on construction sector (Biton & Howell, 2013), reviewed the lean implementation in construction sector (Olivieri et al., 2018) , and also explored the gaps of the transition from lean manufacturing to lean construction (Jørgensen & Emmitt, 2008), whilst some of these reviews focused on specific aspects such as sustainable development by lean construction (Bae & Kim, 2008) , the concept of value in construction industry (Salvatierra-Garrido & Pasquire, 2011) , waste in construction project (Viana et al., 2012), or lean construction tools for accidents management (Bashir et al., 2011). These literature reviews analysed various issues in lean construction from different aspects, but the use of rigorous bibliometric tools can provide additional analysis and further insights of lean construction that were not full mastered.

It should be noted that due to the development of information technology over the years, there are many structured analysis tools which are available to ensure that a systematic review of bibliographic records can be conducted. For example, latent semantic analysis is a method that determines the contextual-usage meaning of words using statistical computations. This approach has been adopted to identify the patterns and trends of BIM (Yalcinkaya & Singh, 2015). Furthermore, machine learning has been adopted to conduct citation sentiment analysis, which can help discover the researchers' opinion on the cited work. For example, citation classification as positive or negative using naïve Bayes classifier was proposed by Sula and Miller (2014). According Li et al. (2017), the benefits of these information technology tools is related to their ability to identify the hidden connections of various developments, which may not be easily identified by manual reviews. Through a search in Web of Science (WoS) using "lean construction" as keywords, a total of 716 articles were identified and reviewed. The 716 publications are analysed through document co-citation, keywords co-citation and citation bursts.

### 2.1.1 Document co-citation network

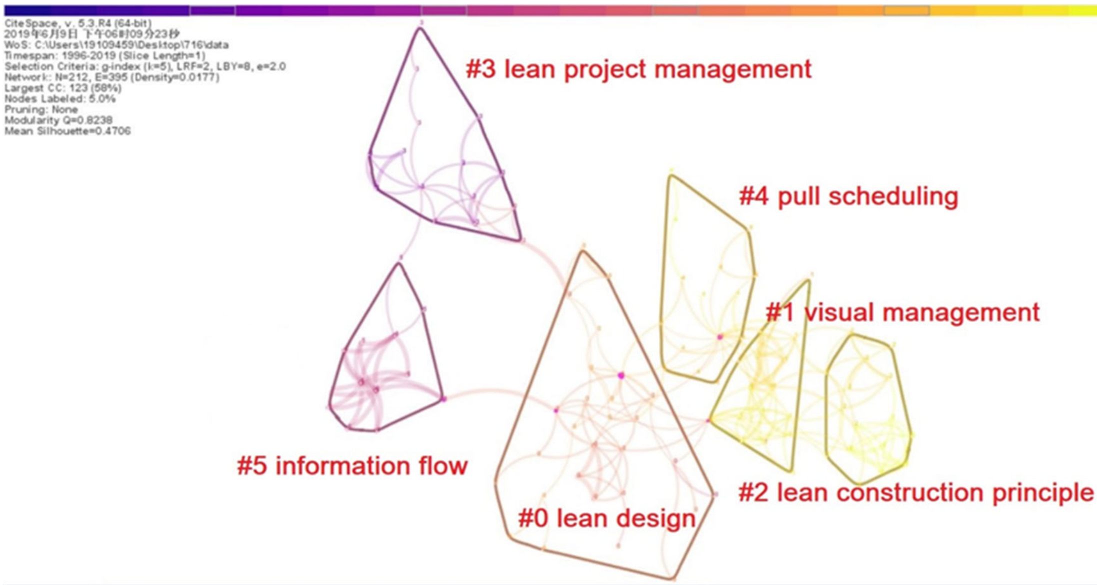


Figure 2-1: Document co-citation network and cluster analysis of lean construction

Co-citation network can be used to identify the clusters of knowledge in lean construction. The network of document co-citation with 212 nodes and 395 links is presented in Fig.2-1. The size of nodes reveals the frequency of co-citation. The links in this network indicate co-citation relationships between two corresponding publications. Publications cited in 716 retrieved records were analysed through co-cited references to explore the underlying knowledge base of lean construction research domain. The top 10 cited publications are shown in Table 2-1. Sacks, Radosavljevic, et al. (2010), Aziz and Hafez (2013), Sacks, Koskela, et al. (2010) received 29, 18, and 14 co-citations, respectively, and are ranked in top three positions. Sacks, et al. (2010) developed a lean production management integrated BIM technology system for improving work flow and reduce waste by visualising construction production and production process. Aziz and Hafez (2013) proved that implementation of lean construction can minimise waste during construction and improve construction management practices. Sacks, Koskela, et al. (2010) developed a conceptual framework for integrating BIM and lean construction. Salem et al. (2006) demonstrated that implementation of lean construction technologies such as LPS, Visualisation Management (VM), and 5S, can have good performance for construction quality. In addition, the publication with high betweenness centrality score needs to be mentioned, because it connects more groups than lower score (Chen, 2014). For example, Garrett and Lee (2010) is 0.23 has the highest score among all the publications. The second one is Erik Eriksson (2010) with centrality of 0.18, which means these two articles has significant influence on the development of lean construction research.

Table 2-1: Top ten critical publications in lean construction

| Author | Title | Year | Citation Counts | Document type |
|---|---|---|---|---|
| Sacks, Rafael, Milan Radosavljevic, and Ronen Barak. | Requirements for building information modeling based lean production management systems for construction | 2010 | 29 | Automation in Construction |
| Aziz, Remon Fayek, and Sherif Mohamed Hafez | Applying lean thinking in construction and performance improvement | 2013 | 18 | Alexandria Engineering Journal |
| Sacks, R., Koskela, L., Dave, B. A., & Owen, R. | Interaction of lean and building information modeling in construction | 2010 | 14 | Journal of construction engineering and management |
| Salem, O., Solomon, J., Genaidy, A., & Minkarah, I. | Lean construction: From theory to implementation | 2006 | 13 | Journal of management in engineering |
| Eastman, Chuck, Paul Teicholz, Rafael Sacks, and Kathleen Liston. | BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors | 2011 | 13 | Book |

| | | | | |
|---|---|---|---|---|
| Dave, B., Kubler, S., Främling, K., & Koskela, L. | Opportunities for enhanced lean construction management using Internet of Things standards | 2016 | 10 | Automation in construction |
| Eastman, Chuck, Paul Teicholz, Rafael Sacks, Kathleen Liston. | A guide to building information modeling for owners, managers, designers, engineers and contractors. | 2008 | 10 | Book |
| Thomas, H. Randolph, Michael J. Horman, R. Edward Minchin Jr, and Dong Chen | Improving labor flow reliability for better productivity as lean construction principle | 2003 | 9 | Journal of construction engineering and management |
| Thomas, H. Randolph, Michael J. Horman, Ubiraci Espinelli Lemes De Souza, and Ivica Zavřski. | Reducing variability to improve performance as a lean construction principle. | 2002 | 9 | Journal of construction engineering and management |
| Garrett, Deborah F., and Jim Lee | Lean Construction Submittal Process-A Case Study | 2011 | 8 | Quality engineering |

Co-citation clusters can improve citation analysis and reveal underlying research trends in the body of knowledge according to the titles, abstracts and index terms of the reference documents by three specialized metrics including term frequency*inverse document frequency(TF*IDF), mutual information tests (MI) and log-likelihood ratio tests (LLR). The best cluster labels results can be selected through LLR method (Chen et al., 2010). 53 co-citation clusters were detected based on the abstract of reference publications. Fig 2-1 shows top 6 significant clusters by LLR tests, and Table 2-2 details co-citation clusters in rank order. The mean year denotes the average year of articles in each cluster. The silhouette score reflects the average homogeneity of a cluster. If the silhouette score exceeds 0.7, the cluster has high reliability and is consistent enough (Zhong et al., 2019). “Lean design (#0)” is the largest cluster with 29 members, “information flow (#6)” is the smallest cluster with 10 members, “lean project management (#3)” is the oldest cluster with 15 members, and the youngest cluster is “lean construction principle (#2)” with 16 members. Each research theme is given in details as follow.

Table 2-2: Top ranked clusters in lean construction

| ID | Size | Silhouette | Label(LLR) | Label(LSI) | Label(MI) | Mean (year) |
|---|---|---|---|---|---|---|
| 0 | 29 | 0.841 | Lean design (2064.11, 1.0E-4) | Lean construction | real world (0.15) | 2006 |
| 1 | 17 | 0.839 | Visual management (2589.7, 1.0E-4) | Lean construction | transportation sector(0.09) | 2012 |
| 2 | 16 | 0.846 | Lean construction principle (1223.06, 1.0E-4); | Lean construction | insufficient benefit (0.09) | 2013 |
| 3 | 15 | 0.925 | Lean project management (1009.8, 1.0E-4) | Lean production | lean project management (0.03) | 2000 |
| 4 | 12 | 0.752 | Pull scheduling (723.2, 1.0E-4); | Lean construction | Lean construction (0.03) | 2001 |
| 5 | 10 | 0.947 | Information flow (607.32, 1.0E-4); | Construction | lean construction (0.03) | 2004 |

Lean design (#0) is the largest cluster with 29 members, which targets at the use of lean theory in the construction sector. Salem et al. (2006) used lean tools such as LPS, VM, and 5S to assess the effects of each technique on construction industry performance and compared such techniques development between manufacturing and construction. In the construction sector, the upstream of lean thinking need to produce significant potential to drive value through the construction process. Garrett and Lee (2010) adopted VSM as one of effective lean tools to analyse construction submittal process and found that lean implementation in construction is effective for waste reduction.

Visual management (#1) is fundamentally an information management system to improve the effectiveness of communication with visual tools and techniques. Tezel and Aziz (2017) discussed that the novel computer-aided techniques such as Internet of Things (IoT), VR, and Laser Scanning can support conventional visual management tools and techniques to enhance lean construction on construction sites. For example, Dave et al. (2016) demonstrated that Internet of Things (IoT) can enhance lean construction service, while improving the information flow throughout the construction project. VisiLean (Dave et al., 2013) as emerging lean construction system has been used to help visualise the construction process with waste elimination. In addition, BIM based visualisation system is also an effective tool on providing work flow transparency in construction industry (Sacks et al., 2009).

Lean construction principle (#2) is the youngest cluster, which includes 16 publications. These studies are focused on the investigation of lean principles that can maximise performance across the construction project lifecycle from design to delivery with lean tools. As Bajjou et al., (2017) stated, LPS, VM, 5S, VSM, BIM, poka-yoka and just in time (JIT) are the most suitable lean techniques and tools for construction firms. Lean construction principle has been widely adopted by building industry to reduce the construction costs and improve productivity (Marhani et al., 2013), including determining value from the customer' point of view, the value stream definition, waste reduction, flow of work processes, pull planning and scheduling and continuous improvement.

Lean project management (#3) is the oldest cluster with 15 members. The representative article is Thomas et al., (2003), which focused on the investigation of effects on lean implementation in three bridge construction projects and the results show that effective flow management can make better labour performance in construction project. Another key term in this cluster is lean production that analysed by LSI method. Lean production is new management thinking that focuses on eliminating or reducing non value added activities to the production. For example, unnecessary travel, waiting, reworks, etc. In addition, variability is the main explanatory variable in the construction industry (Brodetskaia & Sacks, 2007) and the variability of construction workflow can impede construction performance. Thomas et al., (2002) investigated that workflow variability reduction through lean thinking can improve labour performance in construction project. This cluster of lean project management covers early stage that lean theory is effectively applied from manufacture to construction industry for performance improvement.

The cluster of pull scheduling (#4) has almost the same time span with lean project management. Pull scheduling is part of daily management and reporting construction process, which aims to design construction procedures for waste minimisation and value maximization. Integration lean construction to traditional Critical Path Method (CPM) scheduling can improve crew flow and work flow and optimize processes for construction project (Huber & Reiser, 2003). Also, construction site can be organised through lean construction and automatically support daily schedule of the site manager (Binninger et al., 2017).

The cluster of information flow (#5) has similar time span with lean design and the representative publications are "Building Information Modelling Handbook" by Eastman et al., (2011) and "Lean Thinking: Banish Waste and Create Wealth in Your Corporation, Revised and Updated" by (Womack, & Jones, 2003). These studies are related to the needs of information exchange between construction participants with high efficiency. Also, this cluster is an emerging trend that focuses on integrating lean construction with new information technologies such as BIM in construction practices. For example, Al Hattab and Hamzeh (2017) demonstrated that the design of lean and BIM based information flow shows the efficiency gains for wastes elimination in building design.

### 2.1.2 Keywords co-citation network

Keywords co-citation was analysed with Citespace. Such analysis can reveal the hot topics in lean construction. As can been seen from Figure 2-2, the network included 167 nodes and 478 links. The frequency of terms is shown in Table 2-3. Some of the key terms are discussed as follows. The term of "performance" is an important research topic with 58 frequencies for lean construction. Lean management are used to improvement construction performance or outcome to achieve the high quality in construction industry. A performance evaluation is therefore necessary for any lean construction related study.

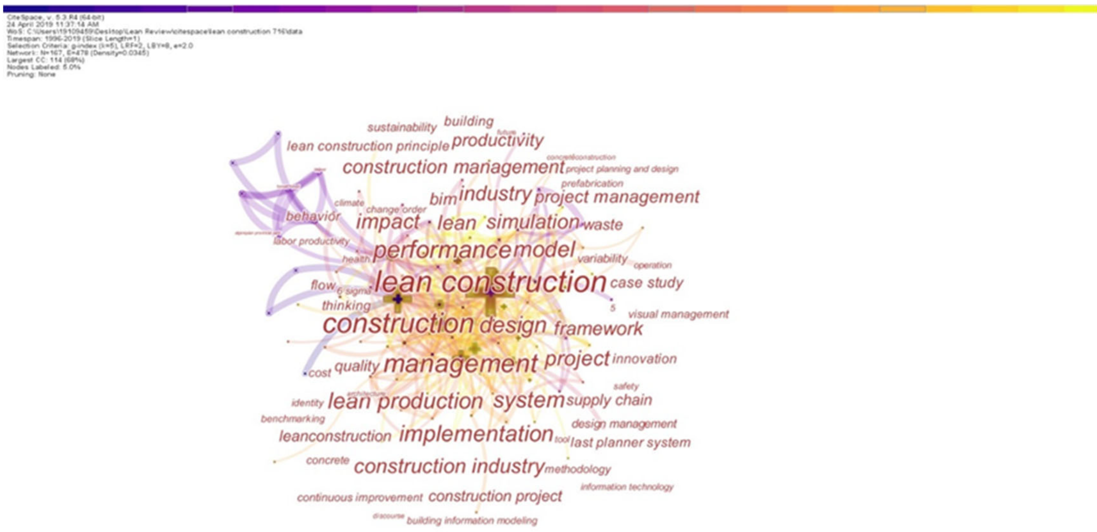


Figure 2-2: keywords co-citation network

Table 2-3: Top keywords with frequency in Lean construction

| Frequency | Keywords | Frequency | Keywords |
|---|---|---|---|
| 163 | lean construction | 10 | variability |
| 92 | construction | 9 | flow |
| 68 | management | 9 | case study |
| 58 | performance | 9 | building |
| 44 | design | 9 | thinking |
| 40 | system | 9 | methodology |
| 37 | Lean production | 9 | technology |
| 37 | model | 8 | risk management |
| 36 | implementation | 8 | cost |
| 36 | project | 7 | behavior |
| 31 | simulation | 7 | Value stream mapping |
| 30 | lean | 7 | six sigma |
| 30 | impact | 7 | organization |
| 26 | industry | 7 | information technology |
| 23 | productivity | 7 | concrete |
| 22 | construction industry | 6 | work |
| 21 | framework | 6 | Building information modeling |
| 20 | construction management | 6 | supply chain management |
| 20 | waste | 6 | Labor productivity |
| 20 | project management | 6 | production management |
| 18 | supply chain | 6 | design management |
| 14 | quality | 5 | operation |
| 14 | bim | 5 | visual management |
| 13 | sustainability | 5 | safety |

| | | | |
|---|---|---|---|
| 12 | innovation | 5 | trust |
| 12 | construction project | 5 | tool |
| 11 | lean manufacturing | 5 | continuous improvement |
| 11 | lean construction principle | 5 | value |
| 11 | lean thinking | | |
| 11 | Last planner system | | |

In the construction sector, "Design" for lean construction means that lean application on construction development accomplishes the design management field of construction work. It has significant influence on the quality of construction project. Jørgensen and Emmitt (2009) demonstrated that design of lean construction can be applied to construction management system to generate value activities and reduce waste in building project. According to Reifi and Emmitt (2013), interaction, value, lean culture and information flow are four dominant topics that are correlated with waste reduction and value improvement in lean design management.

Implementation of lean construction is also a major research topic. Some studies argued that construction work is different because of many uncertainties and constraints to make construction operation more like manufacturing process through consummate standards (Howell & Ballard, 1998; Sarhan & Fox, 2013). The positive effects on lean implementation are also presented, such as minimising the risk effects on construction schedule (Issa, 2013) and productivity improvement (Aziz & Hafez, 2013). However, the main barriers to successful implementation of lean construction are lack adequate lean awareness and understanding, cultural and personnel attitude, and lack of commitment from senior management. (Sarhan & Fox, 2013).

Simulation is another important research topic with 31 co-occurrence frequencies. Many construction workers rely on simulation when planning and implementing lean to completely eliminate waste. Many studies also used 3D simulation modelling to demonstrate that lean concepts such a JIT, Total Quality Management can improve productivity and reduce the duration of construction projects (Goh & Goh, 2019).

Supply Chain or Supply Chain Management are critical topics for lean construction. Supply chain in construction projects could include all participants in construction project such as architects, engineers, and contractors to achieve construction objectives for short-term business. Lean practice has been adopted in the construction sector for supply chain performance improvement (Erik Eriksson, 2010). Lean practices in construction focuses on the supply chain to improve customer satisfaction and elimination waste by using tools, performance metrics and management strategies. Naim and Barlow (2003) used lean production in house-building industry for supply chain management and discovered a positive impact. As Meng (2019) stated, supply chain collaboration should be integrated with lean construction to achieve optimal supply chain performance.

Building information modelling (BIM) brings a revolution to lean construction. Lean construction can be facilitated through BIM. For instance, a simulated model of construction project sequence can be added as an essential part of collaborative planning for visual management. With the rapid development of mobile device, it is possible to directly deliver BIM information to client or engineer to allow viewing related construction information during a collaborative planning session. The synergy between lean construction and BIM can enable easier identification of values to client, not only in the design and construction stage, but over project life-cycle.

### 2.1.3 Keywords with the strongest citation bursts

Citation bursts usually indicate that a potentially interesting work has attracted extraordinary attention in a short period time (Chen, 2014). Figure.2-3. lists the top 10 keyword citation bursts. The strongest citation burst is “lean construction” (strength=7.3892, 2012-2013), and “lean production” (strength=6.9897, 2008-2013) is the second strongest citation burst, followed by “construction industry” (strength=6.3629, 2002-2013). In recent year from 2016-2019, “implementation” (strength=5.4939), “supply chain” (strength=5.0341) and “framework” (strength=4.1275) are the strong citation bursts, indicating that these keywords are the

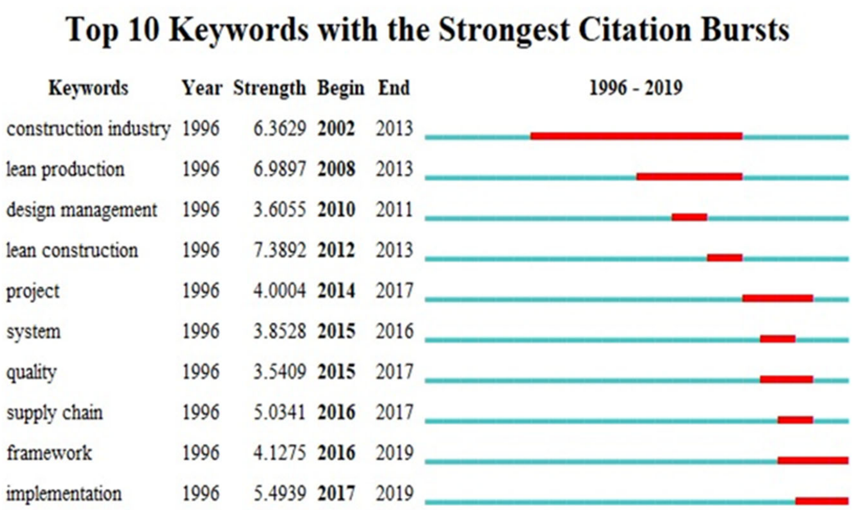


Figure 2-3: Top 10 Keyword with the strongest citation bursts

popular topic in lean construction field in those years. The results in Figure.5-3 also show the development of lean construction research over time.

## 2.2 Lean for education and training

The lean philosophy originated from the Toyota Production System (Krafcik, 1998), 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 (Myerson, 2012). Lean education is the adaption of lean thinking to identify and solve educational problems and improve learning and teaching activities. Antony and Douglas (2015) translated eight wastes of lean manufacturing to the education sector, as shown in Table 2-4. Lean implementation in education can help reduce cost and educational cycle time, as well as increase the satisfaction level for students, overall learning process (Vukadinovic et al., 2017) student academic experiences, and productivity (Simmons & Young, 2014). 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 (Alves et al., 2016).

Table 2-4: 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 (Mansur et al., 2017) | Construction task is completed faster than scheduled or before it is required in the process (Bajjou et al., 2017) |
| Waiting | Time spent on idling for the | Knowledge acquired by students must be | Typically occurs when a worker is ready, but |

| | | | |
|---|---|---|---|
| | next process step to occur | retained until the following subject in the learning process (Morien 2019) | the materials required for work have not been delivered, or the previous task has not been completed (Polat & Ballard, 2004) |
| 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 (Mansur et al., 2017) | Materials, equipment, or workers are moved from one job site to another before they are required (Lee et al., 1999) |
| Overprocessing | Waste owing to more work than that required by the customer | Excessive inappropriate teaching and learning processes for students (Pavlović et al., 2014) | Overprocessed construction activities that have no value to the customer ( Nahmens & Ikuma, 2014) |
| 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 (Morien 2019) | Unnecessary movements by workers to accomplish their work, which do not add value to the customer (Abdelhamid & Salem, 2005) |
| 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 (Mansur et al., 2017) | Materials stored on the construction site that are not required immediately (Conte & Gransberg, 2001) |
| Defects | Waste from a product or service fails to satisfy customer expectations | Shallow learning and failing to understand the related subject matter (Pavlović et al., 2014) | Defects in construction are incorrect work requiring rework or repair (Setijono & Aomar, 2012) |
| Unused talent | Waste owing to failing to | Failing to recognize the ideas and | Workers who have extensive experiences |

| | | | |
|---|---|---|---|
| | utilize human talents, skills, and knowledge | suggestions of teachers and students for improvement (Morien 2019) | or skills are not matched to the right jobs on construction sites (Ismail & Yusof, 2016) |

As shown in Table 2-4, the lean concept has been successfully used by construction companies to reduce project costs and waste on construction sites (Anderson & Kovach, 2014; Marhani et al., 2013). Over 40 lean techniques and tools have been adopted in lean construction (Ansah & Sorooshian, 2017). According to the study by Bajjou et al., (2017), the most typically adopted lean tools for the construction industry include 5S, (JIT), poka-yoke, and VSM. The definitions of related lean tools and applications are shown in Table 2-5. 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 (Lu, 2017; Sfakianaki & Kakouris 2019). In addition, applying lean concepts in construction operations is still new, demonstrating strong research needs in this area (Vukadinovic et al., 2017).

Table 2-5: 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 (Filip & Mărăscu-Klein, 2015). |
| 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 (Ansha & Sorooshian, 2017). |
| Poka-yoke | Poka-yoke, a Japanese term, is a mechanism to help operators avoid errors (Dudek-Burlikowska & Szewieczek,2009). |
| Value stream mapping (VSM) | VSM is a lean management method for visually analyzing and improving workflow circulation (Bajjou et al., 2017) |

## 2.3 Lean and health and safety

It should be noted that some studies pointed out that the adoption of lean has positive impact on operational health and safety performance. For example, Nahmens and Ikuma (2009) found that lean implementation can reduce accident rates during construction process. Such conclusion was drawn from a survey of 67 builders in the U.S. construction industry. In addition, Wu et al. (2019) developed a conceptual model that contains five types of lean tools, which are 5S management (sorting, consolidation, sweeping, cleaning and quality), visual management, Last Planner System (LPS), Just-in-time management and conference management, and demonstrated that lean practices could play a significant role in improving health and safety in construction. This was obtained through a questionnaire of investigating the relationship between the five lean tools and safety planning, compliance, participation and inspection. Similarly, Gambatese et al. (2016) evaluated the alignment between lean principles and the worker safety behaviour through content analysis and expert panel discussion and argued that lean practices, such as the use of LPS, has potential benefits towards safety practices. It should be noted that previous studies investigating the relationship between lean and occupational health and safety are mainly based on surveys, questionnaires and panel discussions. A quantitative examination of the potential improvement in occupational health and safety was not observed in these studies. Some other studies attempted to provide such quantification. For example, Ikuma et al. (2010) evaluated the increase in value-added activities and outputs of modular homebuilding and argued that because the improvement is caused by quicker and reduced process, safety and ergonomic hazards can also be appropriated improved and managed.

## 2.4 Value stream mapping

The traditional approach of TAM process improvement focuses on isolated process (Shou et al., 2019;). Once problem is identified in a specific process, improvement options will be evaluated. The overall impact on the entire value stream is usually overlooked (Shou et al., 2015). VSM, as a method of focusing on the entire value stream, has therefore been gradually recognized in recent years. Many studies have been conducted to analyse VSM implementation in construction projects. For example, Rosenbaum et al. (2013) adopted VSM method to visualise the production and environmental waste by mapping construction processes and reveal the opportunities of performance improvement in the structural concrete construction. Pasqualini and Zawislak (2005) used VSM to identify construction problems and process wastes and propose actions for improvement throughout the value flow in construction industry. It appears that TAM process, which share many similarities with construction process, can also be the target for VSM improvement. According to Shou (2018), TAM activities can be classified into value added activity, non-value added activity, and non-value added activity but necessary. Value added activity is the activity that directly transforms construction in construction site, such as scaffolding components installation. Non-value added activity refers to waste that does not increase the value of what is delivered to the customer. These activities may include rework and unnecessary waiting. Non-value added activity but necessary is the activity must be done, but they add no value, such as checking activities. Such classification is therefore adopted in this study.

### 2.4.1 VSM in construction

Lean concept has been successfully adopted by construction companies to reduce project costs and waste on construction sites (Anderson & Kovach, 2014; Marhani et al., 2013). In addition, it is believed that the adoption of lean practice has a positive impact on construction health and safety (Gambatese et al., 2016; Longoni et al., 2013) and productivity (Ikuma et al., 2010), also construction accident rates (Nahmens & Ikuma, 2009). Total productive maintenance (TPM) is a plant improvement tool used to achieve lean maintenance for avoiding waste and productivity improvement. Studies have confirmed that TPM has strong significant impact on industry maintenance performance. For example, Ramakrishnan and Nallusamy (2017) demonstrated TPM implementation can reduce the overall breakdown hours in manufacturing industry, and have a positive effect on improving the work culture of employees. Méndez and Rodriguez (2017) stated that TPM is an effective strategy for improving productivity in automotive industry. In addition, maintenance programmes such as routine maintenance, scheduled maintenance, continuous improvements, quality maintenance, trainings of people, safety and health environmental considerations, equipment management, can be linked by TPM strategy to achieve high level of overall equipment efficiency (Ng et al., 2017). VSM is a lean technique that has been adopted in construction and it helps identify the current value stream and eliminate waste in the value stream to reach a lean future state. Lacerda et al. (2016) described that VSM implementation in the manufacturing field is crucial for the reduction of waste and process improvement. Tyagi et al. (2015) used VSM based method to eliminate the wastes, inefficiencies and non-valued-added activities for product development performance improvement in a gas turbine manufacturer. VSM has also been used to improve the sustainable performance of construction projects by reduce resource consumption and cost (Rosenbaum et al., 2013).

VSM is an effective tool that helps customer visualise and understand the flow of material and information through a value stream. VSM helps improve the entire process flow in four steps (Rother & Shook, 2003). The product family, as the target for improvement, is selected at the beginning of the study as the first step. The second step is to draw a current state map (CSM) by capturing the whole material and information flows. It helps customer visualise the sources of waste in value stream and describe these in details. The third step is to produce a future state map (FSM) based on the elimination of the non-value adding activities that have been identified. The last step is to implement the proposed changes by identifying opportunities for process improvements to achieve the project objectives. The improvement is often assessed based on a few criteria, which may include lead time (LT), processing time (PT), value added time (VAT), waiting time (WT), etc. Table 2-6 presents the indicators and their definitions that are commonly adopted to evaluate lean performance improvement.

Table 2-6: Key Indicators in VSM evaluation

| VSM Key Concepts | Definitions | References |
|---|---|---|
| Lead time (LT) | LT is the time that takes one piece to move all the way through a process from start to finish. | (Rother & Shook, 2003; Seth* & Gupta, 2005) |
| Processing time (PT) | PT is the time that one product spends in a process step. | (Jeong & Yoon, 2016) |
| Value Added time (VAT) | VAT is the time that actually transform the product in a way that the customer is willing to pay for. | (Tyagi et al., 2015) |
| Waiting time (WT) | A delay in processing caused by waiting. | (Heravi & Rashid, 2017; |

| | | |
|---|---|---|
| | | Rother & Shook, 2003) |
| Cycle time (CT) | How often a product is completed actually by a process. | (Barathwaj et al., 2017; Seth* & Gupta, 2005) |
| Inventory | A detailed list of all the items. | (Shou et al., 2017) |
| Manpower | The force of workers available. | (Yu et al., 2011) |
| Up time percentage | The percentage of available production time that is actually on construction. | (Nahmens & Ikuma, 2011) |
| Performance | The progress obtained by a determined amount of worker hours. | (Tuli & Shankar, 2015) |
| Setup time percentage | The proportion of setup time over the duration of a given activity. | (Tabanli & Ertay, 2013) |
| Material waste | Amount of material waste in comparison with the amount needed. | (Lacerda et al., 2016) |
| Percent started on schedule | The percentage of start-date promises that are delivered on time. | (Sunk et al., 2017) |
| Yield | The proportion of construction that go through an operation correctly, without rework. | (Shou et al., 2017) |

### 2.4.2 VSM for engineering education and training

Among all available lean tools for engineering education and training, VSM has proven to be 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 (Rosentrater & Balamuralikrishna, 2006). Lobaugh (2008) used VSM to analyze the information flow of manufacturing processes in engineering fields for waste elimination. Steinlicht et al., (2010) 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.

## 2.5 The use of VR in construction engineering education and training

VR technologies have been rapidly recognized in construction engineering education and training (CEET) programmes because they are believed to be effective in enhancing the quality of such programmes. A representative taxonomy of the visualisation system for positioning VR was originally made by Milgram and Colquhoum (1999), and describes how "virtual" and "real" are merged in different proportions for creating a visualisation environment. There are four different levels on the reality-virtuality (RV) continuum to be defined: Pure Real Presence, Augmented Virtuality (AV), Augmented Reality (AR) and Pure Virtual Presence. Strictly speaking, VR technologies are those visualisation techniques referred to pure virtual presence, and nowadays are attracting much attention for improving communications in professional work and shared spaces. Benford et al., (1998) introduced a classification of shared spaces based on their transportation, artificiality and spatiality. They can be categorized as media spaces, spatial video-conferencing, collaborative virtual environments, telepresence systems and collaborative augmented environment. Most of them have adopted different levels of VR involvement in recent years. There are many studies which have demonstrated the positive impact of VR in such adoptions (Woksepp & Olofsson, 2008; Goedert & Rokooei, 2016). Goedert and Rokooei (2016) developed a virtual interactive construction education platform which provided game-based safety training through the use of simulation and modelling. The advantages of using VR in education and training are related to its ability to enable students to interact with each other within virtual three-dimensional (3D) environments. Intuitive sense about the learning subjects can also be developed by interacting with the objects, related messages and signals in the virtual environment. Different from the conventional education and training approaches, such as the utilizations of static pictures or two dimensional (2D) drawings, VR's visual representation allows more degrees of freedom (DoFs) to be integrated.

Since the early 2000s, various visualisation techniques, such as VR and its sibling development, AR, have been adopted to enhance learning experiences. VR, as an effective tool, has proven to be effective for providing better understanding and visualisation capabilities. For example, in architectural education and training, students can perceive different architectural spaces through a 3D object, rather than viewing traditional drawings. In addition, the education and training using traditional 3D approaches relies on the use of a mouse or keyboard to interact with the computer-generated structural form. However, in the VR environment, the immediate results of interactive activities, such as pulling and grabbing, can be visualised in a real-time manner (Park et al., 2015).

Due to the rapid changes in the technologies adopted in industry, providing sufficient training programmes to improve the daily activities of employees has played an important role. Traditional training programmes, such as computer-based learning, are unable to equip decision makers to deal with various situations. In addition, for projects which significantly value productivity (such as oil and gas plant maintenance), on-the-job training is not possible because on-site work conditions are usually not revealed until the maintenance project begins. VR has therefore been promoted to address these practical problems in education and training.

VR has also been integrated with other enabling technologies to further enhance the performance of construction education and training. In the construction industry, there has been a rapid development of Building Information Modelling (BIM) (Wang et al., 2014; Li et al., 2017; Wang et al., 2018). One of the benefits of BIM is related to its effectiveness in improving the performance of education and training. For example, Russell et al., (2013) argued that the BIM technology is useful to train students on the skillful use of 3D modelling techniques, which are believed to replace the traditional computer-aided design (CAD). Following the development of BIM, Augmented Reality (AR) is now very commonly adopted as well to support interactive visualisation (Wang et al., 2014). One major benefit of AR is the provision of engaging, motivating and immersive contents. As Chen et al., (2011) pointed out, such contents are able to help students better understand their interactions with the 3D objects.

Despite the rapid development of VR and other enabling technologies, there have been limited studies on a systematic investigation of the development and its implementation in construction engineering education and training (Guo et al., 2012). Although VR has already been adopted in architecture engineering and construction education (Hong et al., 2016; Fonseca et al., 2014; Young et al., 2011; Pedro et al., 2015), the use of a head-mounted display (HMD) can cause problems such as discomfort and poor depth perception (Kerawalla et al., 2006). To avoid these problems, portable technologies that are less immersive and present have recently been developed (Shirazi & Behzadan, 2014; Fonseca et al., 2016). More importantly, the use of VR does not necessarily involve education and training pedagogy. It appears that there is a large research gap related to a systematic investigation on the development and use of VR in education and training (Wu et al., 2013)

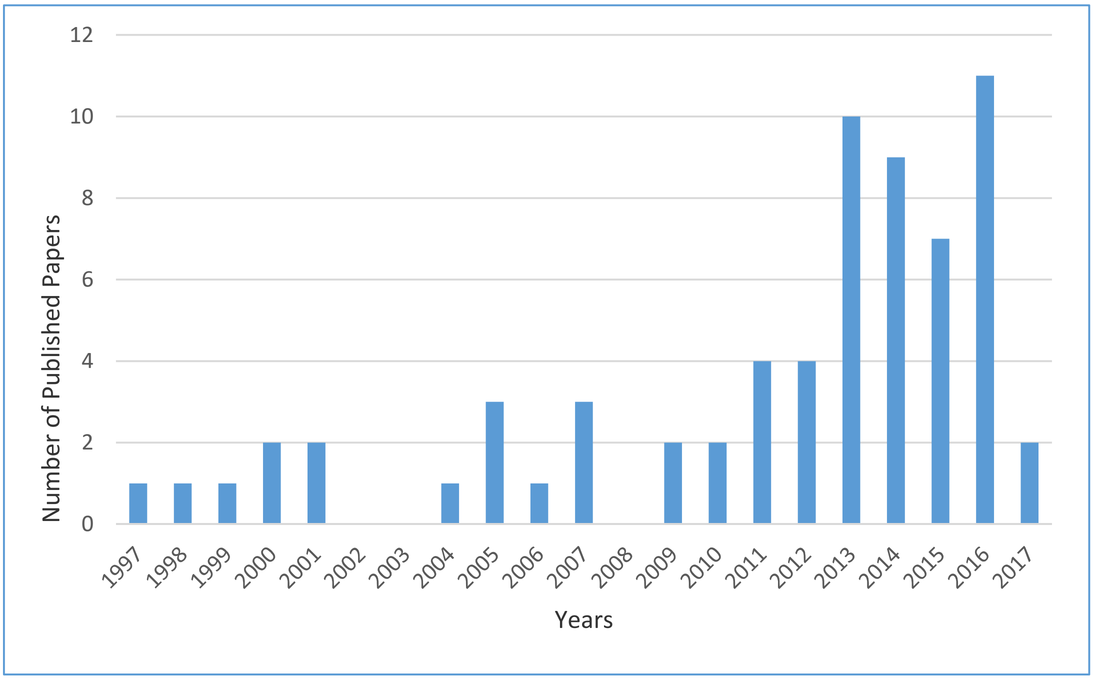


Figure 2-4: Number of publications on VR and its implementation in CEET from 1997 to September 2017.

Figure 2-4 shows the number of publications characterized by publication year, indicating that research interest on VR and its implementation in CEET has been increasing since 2013. Some notable publications in year 2013 are: Location tracking and data visualisation technology to advance construction ironworkers' education and training in safety and productivity (Teizer et al., 2013), which presented a novel real-time location tracking and data visualisation in worker training environment, and A framework for construction safety management and visualisation system (Park & Kim, 2013), which proposed a framework for visualisation system to enhance capacity of workers on construction site.

Table 2-7 presents the distribution of selected publications characterized by the publication venues. Over 24 journals containing articles related to VR in CEET were identified. As can be seen from Table 2, Journal of Professional Issues in Engineering Education and Practice and Automation in Construction are the most two popular venues for VR in CEET. Some notable publications in the Journal of Professional Issues in Engineering Education and Practice are: Use of tangible and augmented reality models in engineering graphics courses (Chen et al., 2011), and BIM-enabled virtual and collaborative construction engineering and management (Burcin et al., 2012).

Table 2-7: Distribution of the selected journal papers by publication venues

| Journal title | Number of Selected Papers |
|---|---|
| Journal of Professional Issues in Engineering Education and Practice | 11 |
| Automation in Construction | 8 |
| International Journal of Engineering Education | 6 |
| International Journal of Construction Education and Research | 5 |
| Computer Applications in Engineering Education | 5 |
| Electronic Journal of Information Technology in Construction | 4 |
| Journal of Information Technology in Construction | 4 |
| Practice Periodical on Structural Design and Construction | 4 |
| Journal of Architectural Engineering | 2 |
| Journal of Construction Engineering and Management | 2 |
| Engineering Design Graphics Journal | 2 |
| Journal on Educational Resources in Computing | 1 |
| Advances in Engineering Software | 1 |
| Architectural Engineering and Design Management | 1 |
| Australasian Journal of Construction Economics and Building | 1 |
| Australasian Journal of Engineering Education | 1 |
| Behaviour and Information Technology | 1 |
| Computers and Education | 1 |
| Computers in Education Journal | 1 |
| Journal of Computing in Civil Engineering | 1 |
| Journal of Engineering, Design and Technology | 1 |
| Journal of Industrial Technology | 1 |
| Materials and Structures | 1 |
| Simulation | 1 |
| Total | 66 |

### 2.5.1 VR and related technologies in construction engineering education and training

VR and related technologies in CEET can be categorized into five major types, including desktop-based VR, immersive VR, 3D game-based VR, BIM-enabled VR and Augmented Reality (AR). This is categorized based on the different uses of visualisation media as well as those of display platforms. The focus of the study is placed on the observations of related VR technology developments and their evaluations under CEET programmes. It should be noticed that the categorization is enumerated, but does not limit further considerations covering all perspectives related to VR, including hardware, software, visualisation and interaction issues. The detailed taxonomies of VR, as well as virtual environment systems, can be referred to in Milgram and Colquhoum (1999), and Stanney and Hale (2014). Table 4-2 presents the distribution of the selected publications characterized by the technologies that are adopted. As can be seen from Table 2-8, the most commonly adopted VR systems in the literature are BIM-based VR and desktop-based VR, accounting for 47% and 26%, respectively. However, while the development of desktop-based VR is relatively stable, the development of BIM-based VR technology and AR has attracted much attention in recent years, with 27 and 7 publications respectively.

Table 2-8: The distribution of publications characterized by technology and publication year.

| Research Theme | Period | | | | Total | Percentage |
|---|---|---|---|---|---|---|
| | 1997–2001 | 2002–2006 | 2007–2011 | 2012–2017 | | |
| Desktop-based VR | 6 | 3 | 3 | 5 | 17 | 26% |
| Immersive VR | 1 | 1 | 1 | 1 | 4 | 6% |
| 3D game-based VR | 0 | 0 | 0 | 4 | 4 | 6% |
| BIM-based VR | 0 | 0 | 4 | 27 | 31 | 47% |
| Augmented Reality | 0 | 0 | 3 | 7 | 10 | 15% |
| Total | 7 | 4 | 11 | 44 | 66 | 100% |

Desktop-based VR is the most commonly adopted VR technology in CEET in the early stages. As can be seen from Table 2-8, 6 of the 7 studies from 1997–2001 are related to desktop-based VR. According to Chen et al. (2007), the technology uses a simple computer monitor as the platform for accommodating virtual activities. Desktop-based VR displays a 3D virtual world on a desktop screen without any tracking equipment to support. It relies on the users' spatial and perception abilities to experience what happens around them. Most of the tasks can be conducted through the use of mouse and keyboards. As the technology only relies on the use of monitors, keyboards and mouse, it is considered to be relatively cheap when compared with other technologies.

Some of the most notable developments of desktop-based VR are the V-REALISM (Li et al., 2003) and the Interactive Construction Management Learning System (ICMLS), developed by Sawhney et al., (2000). V-REALISM is developed for maintenance engineering training. It uses Computer-Aided Design (CAD) to construct the geometrical models which are then displayed through the OpenGL programming interface. V-REALISM adopts a hierarchical structure for the geometrical models which can facilitate the navigation and operation of the models in the virtual environment. This is considered to be one of the major contributions. Similarly, ICMLS was developed to address the disconnection between education and real-life on-site operations related to the use of construction equipment and methods. According to Sawhney et al., (2000), ICMLS is a web-based system which relies on the creation of virtual models through VR modelling language (VRML) and the demonstration of appropriate operations through discrete-event simulations (DES) and web-based computing. According to Mawlana et al., (2015), ICMLS can clearly provide the needs of on-site construction which can then be embedded into CEET. The development of desktop-based VR is relatively stable, with recent developments focusing on 3D computer models and virtual laboratory to improve students' motivation and comprehension (Vergara et al., 2016; Glick et al., 2012).

Compared with desktop-based VR, immersive VR relies on the use of special hardware, such as the head-mounted device (HMD) and sensor gloves, to withdraw users from the physical world and provide an immersive environment. Spatial immersion is created by surrounding with images, sounds or other virtual scenarios, user can feel the virtual world is "authentic" and "real." A typical demonstration of immersive VR is provided in Waly and Thabet (2003), who developed the Cave Automatic Virtual Environment (CAVE). An immersive virtual environment is created around the position of the user's location. As the position of the user changes, his/her position in the virtual environment also changes. In addition, various sensors can be embedded in the accessories of the participants, e.g., the gloves and suits to offer real-time feedback (Ausburn L & Ausburn F, 2004; Hutchinson & Kuester, 2004). Due to the real-time capabilities, immersive VR is believed to be advantageous over the desktop-based VR system (Sacks & Pikas, 2013).

Another typical immersive VR system is the virtual structural analysis programme (VSAP), developed by the Virginia Polytechnic Institute and State University (Setareh et al., 2005). According to Setareh et al., (2005), the main use of the system is to understand the structural behavior of buildings in a virtual environment. The main contribution of VSAP is the development of a portal immersive interface because the traditional immersive interfaces have high cost and while desktop interface has low cost, it sacrifices the quality. An adapted Virginia Tech CAVE (VT CAVE) was therefore developed with a 3 m × 3 m × 2.75 m cubic room. VT CAVE is proved to be effective in terms of usability.

In order to provide immersive feelings to the users, immersive VR can have more supportive control tools especially tracking equipment for interactions, such as game controllers and motion tracking devices. They are commonly adopted to detect and demonstrate the movements of subjects in the virtual environment. Sacks et al., (2013) used a 3D immersive VR power-wall for construction safe training education. The setting of the power-wall consisted of three rear-projection screens, and it is an open configuration of three-sided CAVE that uses 3D stereo projection with active glass. The trainees used a head tracking system and XBOX controller (2018) that was also tracked using eight cameras mounted on the tops of the screens. Three software tools were used, the building demonstrated in the system was modelled in Autodesk Revit (2017), other 3D geometry was modelled using 3D Studio MAX (2018), and the VR scenarios were generated with EON Studio v6 (2018). The results show that VR-based training was more effective in improving concentration and giving trainees a measure of control over the environment.

3D game technology, which aims to enhance user interactions, refers to computer-based game-like training scenes through integrating visual, interactive, network and multi-user operating technologies and so forth. As game-based training, it can be used to enhance collaboration and interaction among students through the provision of tasks that are useful and close to real-life operations (Dickinson et al., 2011; Lin et al., 2011; Li et al., 2012; Nikolic et al., 2015). Other than focusing merely on the immersive effect, game-based VR focuses more on game objects' interactions. For example, collision reactions can be precisely described through a physics simulation module in a game engine. In 3D game-based VR, simplified collision boundary and ray tracing methods are adopted to reduce the complexity of detection processes. In this case, game objects should be defined by both their geometric properties and collision boundaries. For complex objects such as construction excavator or cranes, it helps reduce the complexity and can make “collision detection” computationally easier.

For example, Guo et al., (2012) developed a game-based safety training system, which is an online platform that allows trainees to use input devices, such as keyboard, mouse and game controllers (i.e., Wii (2018) in this case) and so on, to operate virtual tasks, such as equipment operation and material delivery. The main advantage of the system is related to the availability of repeated trials at a rather low cost. For example, different methods and schedules to operate the equipment can be tested through the use of the game-based approach. Through the testing, the potential issues, e.g., health and safety considerations, can be identified. In addition, Le et al., (2016) developed a game-based training platform for managing construction defect. The virtual components are created through the use of Revit Architecture and close-to-reality defect scenarios are represented with the assistance of Linden Scripting Language. In this platform, the students are trained with defect knowledge. They will then be invited to identify defects and possible activities that can lead to defect in various scenarios, the test outcomes show positive in terms of interactivity and performance.

BIM is related to the creation and use of a three-dimensional objects, which also contain relevant properties information (Gheisari &Irizarry, 2016). The relevant properties information particularly referred to that of necessary data required in a practical building project through its entire life cycle, including design, planning, construction, operation and maintenance stages. As such, BIM-enabled VR relies on the model, emphasizing on the data binding and connections behind other than other VR categories, to simulate construction processes and operations. Visualisation is one of the most important characteristics of BIM (Wang et al., 2014). Users can access BIM data in immersive visualisation environment and analyze factors like cost and material type to develop effective building design in real time. By reviewing the design details, all elements of the BIM model from architecture and structure to Mechanical, Electrical and Plumbing (MEP) can be discussed in a more detailed way. For example, BIM-enabled VR allows user to take building design into a 3D virtual environment with all relevant building information, experiencing the BIM model in a virtual environment without the restrictions of peering into a 2D drawings, and actually inspecting the design space. Tools like Autodesk Revit Live (2017) allow trainees to easily move from conventional 2D drawing design scenarios to those in BIM-based VR interactive environments, maintaining the integrity of building management data in the virtual environment before the building is actually built to understand how all of the design elements will come together. One of the biggest advantages of BIM-based VR is the ability of the model to reflect real-time changes. Xie et al., (2011) pointed out that traditional VR models that are created by VRML may have difficulties in incorporating real-time information. Such difficulties may be caused by the compatibility issue. In addition, many decision-making tools have also been developed to assist the decision making process. For example, Woodward et al., (2011) developed a software system to combine 3D models with schedule information so as to visualise the construction work on site. Park et al., (2015) developed an interactive building anatomy modelling (IBAM) system. The system enables students to interact in a VR environment with building elements. An embedded question-and-answer game can also be integrated to enhance the learning experience.

AR uses sensory technology to provide a live direct or indirect view of a physical environment with augmented virtual information. The sensory technology can provide sound, video or graphics. It should be noted that AR and VR are different visualisation technologies. According to the evaluation by Fonseca et al., (2014), compared to a VR environment, AR enables users to interact with objects (including modifying the scale, position and other properties) that fit perfectly into the real environment. As such, many studies argued that AR technology could provide new interaction possibilities and promote active student participation (Ayer et al., 2016; Behzadan & Kamat, 2013; Shirazi & Behzadan, 2015). For example, Chen et al., (2011) used ARToolKit (2018) to develop the AR model to educate the students on their ability to recognize spatial objects. As the AR model is able to project different 3D models in the real environment, it can enhance students' learning (Chi et al., 2013). In addition, as mobile devices are becoming more convenient for learning, many applications have been developed to embed AR in mobile devices. For example, Williams et al., (2014) used a mobile AR (MAR) environment to train users on context-awareness. In addition, a mobile context-aware AR tool, CAM-ART, was developed by Shirazi et al., (2014) for construction engineering undergraduate course. In the CAM-ART AR platform, static extensible mark-up language is used for content definition and JavaScript logic is used to define the interactions between objects. In addition, Kim et al., (2011) developed an AR-based platform to optimize construction process through adjusting equipment operation. The advantages of AR in this research are that the technology enhances visualisation from operators' perspective and surrounding constraints can be identified.

### 2.5.2 Categories of VR application in construction engineering education and training

From the review, almost 50% of the publications about VR applications in CEET are related to architectural visualisation. VR significantly helps students to understand principles of the architectural design as well as professors to explore the students' projects to detect hidden flaws.

Portman et al., (2015) pointed out that the main benefit of using VR in architectural design is the improved graphics, details of modelling, and character modelling delivered through modelling technologies. For example, Yan et al., (2011) demonstrated the use of the BIM game in the architectural design process. In the BIM game, users are able to create avatars with first- and third-person views of the real environment, and use these data to create navigation options. Another benefit of VR in architecture visualisation is that it enables the comparison of different designs at the same time. For example, in the 3D interactive virtual environmental provided by Kamath et al., (2012), students can explore and interact with virtual building. They can also take the CAD data of a building and convert it into a simulation, and modify the objectives as they wish in the simulation. The usage of virtual worlds in the field of architectural education can benefit students in terms of understanding essence of architecture, which can be the first step of their careers.

Construction safety training is the second largest application areas of VR in CEET, with 12 publications (18%). The construction industry is a high-risk industry where the accident rate remains high. Some of the reasons leading to the high risk include limited safety knowledge of on-site employees and lack of safety awareness and training of these employees. Traditionally, construction safety training is provided in a classroom setting with slide presentations or videos. The safety information provided in the presentations and videos often do not represent real construction site conditions

(Saleh & Pendley, 2012; Li et al., 2018). There are limited interactive methods to effectively engage trainees to improve their training performance (Teizer et al., 2013).

A few VR and related technologies, such as BIM, game technologies, and AR, have therefore been developed to improve the current construction safe training practices. For example, Pedro et al. (2015) developed a virtual platform for university students to access safety information through smart devices by scanning QR codes. Although the development of the VR components and the classification of the safety information is considered to be time consuming, the results are found to be promising. Students' motivation and engagement to learn is improved in the VR-based training. Some strategies have also been proposed to address the limitations of time. For example, the BIM objects from previous construction projects can be collected, adapted and stored into a virtual database. In order to raise real-time safety awareness, a framework for safety training and visualisation system (SMVS) that integrates BIM, location tracking, AR and game technologies, is proposed by Park and Kim (2013). The system can provide workers with safety knowledge through mobile device and improve works' safety awareness effectively. By utilizing the system, it could enhance workers' real-time communication ability in unsafe environment. Clevenger et al. (2015) developed a BIM-enabled virtual construction safety training module to evaluate the roles of 3D visualisation in safety training and education in construction. It shows that BIM-enabled safety training is very effective for undergraduate students.

VR has also been implemented in simulating equipment and operational activities. Similarly, traditional construction training on operational activities is based on a classroom environment, followed by on-site training. Although on-site training is considered to be an important step for trainees to gain useful experience, this involves a high risk of injury to the operator and damage to the equipment. Instead, training in a VR-based environment will bring significant benefits in terms of cost and safety. As the training is based on simulation, it does not include commonly seen costs such as fuel consumption and equipment rental. In addition, as the hazardous objects can also be reflected in the virtual environment, the VR-based training can significantly reduce the risks of being exposed to any risk of harm (Su et al., 2013). Some notable developments related to the use of VR in equipment operations includes the multiuser virtual safety training system (MVSTS) (Li et al., 2012), which trains employees on the dismantling procedure of tower cranes. The after-training survey indicates that such method performs better than the traditional training methods. In order to access real-time information for construction safety and operation, Cheng and Teizer (2013) developed a framework that contains real-time data collection and visualisation in construction, it demonstrates that vital safety and operation information can be monitored and visualised for increasing workers' situational awareness.

Although structural analysis is a fundamental subject in engineering, students are usually not too enthusiastic about the subject because of the high level of abstractions and the difficult of understanding the abstractions and concepts in traditional 2D drawings (Chou et al., 1997). Young et al., (2011) investigated the use of 3D visualisation of structures and found that the animation process, e.g., on the stress and strain of structures, can effectively help promote students' learning on structural analysis.

Similarly, Fiorentino et al., (2009) used the AR approach to help student understand Finite Element Analysis (FEA) in structural analysis. In this approach, the FEA results are dynamically demonstrated in the real model as the students changes the properties and characteristics of the simulation. Although the use of VR has its limitations in structural analysis (e.g., the simulation time is largely affected by the complexity of the model), the technology has brought about new perspectives on the education and training of structural analysis.

### 2.5.3 Future research directions of VR in construction engineering education and training

After a comprehensive review of all VR-related articles in CEET, five future research directions are proposed. The validation focuses of those future directions could be put on determining the necessity of VR-related technologies, identifying and evaluating human visualisation and interaction issues, validating the abilities to the systematic integrations in future CEET scenarios.

- **Integrations with emerging education paradigms**

Given the observations from the previous research effort in VR-related CEET applications, none of the research been focused on the other way around; that is, on identifying suitable teaching or learning paradigms for VR environments to cope with under particular construction scenarios, neither for potential interaction issues. As a proposal for a future research direction, different VR technologies can be further evaluated through how they can be systematically integrated with emerging teaching and learning approaches, such as a recently formed education paradigm: flipped classroom (Lai &Hwang, 2016). A flipped classroom is one kind of learning method that requires self-learning actions from students through online teaching material during off-class time, and they thus participate in discussion and team work activities during class. The enhanced interaction between students and objects can help address the passive learning in a traditional classroom setting (Sampaio et al., 2010). What VR can be expected to bring to the flipped classroom includes immersive simulation, multi-user interaction and real-time active learning. With these features, VR-enabled teaching materials can support the development of the flipped classroom to create an active and dynamic learning environment for students. Immersion and interaction are the key factors of VR and can help teachers develop interactive teaching materials for students to perform self-learning activities with sufficient engagement, and cooperative project assignments. The evaluations of integrating such emerging education paradigm with VR technologies and how such integration can benefit all stakeholders in CEET will be a worthy topic that requires further investigation.

- **Improvement of VR-related educational kits**

There is a significant trend in developing new VR devices in order to further enhance the level of immersion and interaction in the virtual environment and reduce the cost, size and perception burdens of human. As can be seen from the current development of VR-related CEET applications, especially equipment and operational task training, there are several mature products in the market which have been widely utilized in the research area of VR education. However, such products still face some limitations. The cost of such products may be high. For example, although CAVE can provide high-resolution images with advanced visualisation as part of the high-quality display system, the cost of such a system is very high. Although the CAVE2 cost has been reduced by 50% compared with CAVE1 in recent years, it still reaches $926K (Manjrekar et al., 2014).

In addition, a fully immersive system should provide a large field of view to offer users real life immersion (Muhanna 2015). However, a few VR technologies, such as shutter glasses, have failed to provide such a large field of view. As such, over the past few years, many studies have been conducted on using head tracking mechanisms to translate movements of the user’s head into virtual camera movements. For example,

Hilfert et al., (2016) showed the possibilities of naturally interacting within a virtual space using an Oculus Rift (2018) head-mounted display and Leap Motion (2018) hand-tracking device. Besides Oculus Rift, there are many VR glasses, such as Microsoft HoloLens (2018) and HTC VIVE (2018), on the market with relatively low prices and great accessibility. In addition, gesture control, such as those brought by Leap Motion, is the most intuitive way to interact with a virtual environment. In Hilfert's (2016) research, it is able to track the student's hands in a real environment, and their movements can be mapped simultaneously in the virtual environment.
These new products have attracted great attention due to their promising capabilities of raising interaction in virtual environments. In the future, research and engineering effort in creating more effective VR toolkits will continue. As such, it seems necessary that these new technologies should be reviewed in a timely fashion for their specific applicability in CEET. For example, the increasing of immersive feeling and dynamic in the virtual environment can also cause more human dizziness when people are exposed to a virtual environment (Clarke et al., 2016). How to design engineering curriculums considering human bodies' reactions should be investigated as a future research direction.

- **VR-enhanced online education**

Based on the review of the previous research, online education is rarely discussed in CEET scenarios. In addition, it is potentially necessary, given that it fits to the nature of cooperation in a construction project, which involves multi-disciplinary roles and a considerable number of stakeholders. They need to put their effort into massive consultation, coordination and communications, which sometimes would be easier and more efficient to perform at distance or in an asynchronous way. Cooperative systems, like BIM, in particular, have nowadays become suitable visualisation and interaction platforms, while the online education of construction engineering is still lacking. In recent years, online education and open universities have become increasingly popular. According to Wu et al., (2013), online or distance learning refers to a learning environment where the students and the classrooms and the teachings are physically separated. Online learning has recorded continuously high growth rates when compared to traditional classroom learning, because it has distinctive advantages in terms of flexibility and accessibility. However, the laboratory components are still found to be difficult to be translated into an online environment, and it is still a big challenge for teachers to help students concentrate on learning through the Internet, which usually involves other distractions, such as social media and online gaming.

VR-enhanced learning has the potential to help online learners engage with the learning process given that it has been successfully employed in conventional engineering education to improve students' spatial skill and concentration (Huang et al., 2015). 3D virtual objects and the interactions with them can attract and maintain the users' attention (Yilmaz et al., 2015). However, the implementation of immersive education in distance learning has not been fully investigated in terms of pedagogy and a systematic design of learning curriculum, especially in CEET scenarios. These are interesting topics which can be investigated in future studies.

- **Hybrid visualisation approaches for ubiquitous learning activities**

Based on the reviewed publications, VR technologies demonstrate featured benefits depending on how realistic the virtual information provided in different CEET scenarios, such as heavy equipment training, design model review and site inspection. In the most of such cases, mobility and solid interactions at training field are still vital. There is a potential research direction in coming up with hybrid visualisation solutions to acquire the sensation of actual presence, e.g., touching, hearing and so forth, along with virtual ones at the same time. Users are encouraging to use VR technologies closely with other visualisation approaches, such as AR, to create a multivariate mixed reality (MR) education environment (Lindgren et al., 2016). With the rapid evolution of other educational kits for facilitating learning activities, the adoptions of mobile and context-aware devices have brought promising results in realising ubiquitous learning environment of engineering education. With the support of wireless networks (Sanguino et al., 2014) and real-time sensing technologies (Chen et al., 2012), ubiquitous environments are transitioning the learning style towards one that can take place anytime and anywhere without the limitations of time and locations (Hwang et al., 2008). Ubiquitous learning environments are expected to exist everywhere not only at home, classrooms or training facilities, but also in the streets and in every corner of cities. For example, field and hands-on learning activities with real-time instructions for structure analysis of building and civil infrastructures have become possible (Huang et al., 2017). Microsoft (2018) has started a promotion of mixed reality environment that makes users feel present in such environment where they can move, interact, and explore in the real world and receive responses in the virtual one. The suitability of the integration of VR and other technologies for CEET activities should be evaluated to maximize the learning performance of students and trainees.

- **Rapid as-built scene generation for virtual training**

Emerging scanning technologies, including reconstruction processes of laser scanned point clouds or photogrammetry (Hou et al., 2014) for captured images, support a rapid as-built modelling in the virtual world, leading cost-efficient and accurate approaches to generate actual scenes for the use of engineering training and education. The level of reality in terms of modelling accuracy, level of detail (LoD) and shading for the as-built 3D model are increasing, as are the related automation processes (Chai et al., 2016). However, no such technologies, according to the reviewed publications, have been used for educational purposes in CEET. Other than facilitating the digitalization of buildings or facilities for construction and management purposes (Omar & Nehdi, 2016), scanning technologies can be used as learning or training materials for students or trainees to get high level of awareness about the content of learning subjects. With the support of these technologies, educators can easily develop the required virtual scenes for CEET activities. For example, it will be much easier to create a realistic and cost effective virtual scene for safety training. Learning resources can also be retrieved from the digitalization processes for BIM and Smart Cities (Anjomshoaa 2015).

## 2.6 Summary

This chapter reviews the literature in order to understand the applications of lean concept and virtual reality in construction and education sector. 716 lean construction-related articles were reviewed by a bibliometric analysis. The analysis of these bibliographic records provides a unique snapshot of lean construction domains and evolution over timespan. In addition, a comprehensive review regarding VR in construction engineering training and education has been conducted and the technologies, application areas and future research directions have been identified. These reveal that VSM as one of lean tools could be integrated into VR training process for training performance improvement. However, research regarding the integration of VSM in VR training is limited and there is a strong research need in this area.

# Chapter 3: Research Methodology

## 3.1 Introduction

The literature review has identified the main problems of this research. This chapter explains the research methodology of this thesis, including method selection, data collection, and data analysis for each objective in this thesis. This chapter is organized in the following structure. Section 3.2 presents research design. Section 3.3 presents research method for Objective1. Section 3.4 presents research method for Objective 2. Section 3.5 presents research method for Objective 3. Section 3.6 presents research method for Objective 4 and Section 3.7 summarises this chapter.

## 3.2 Research design

This research adopts a mixed research method (Figure 3-1). (1) This research starts with a review to identify VR-related research and applications in construction engineering training and education, as well as lean implementations in TAM projects in order to understand how lean, especially VSM can be implemented. (2) In order to identify value adding and non-value adding activities in scaffolding erection in TAM projects, VSM is adopted and Ovako Working Posture Analysis System (OWAS) is adopted to optimise the work flow and work postures to achieve optimal performance of productivity and health and safety. (3) Based on the results from objective 2, an innovative VR- and lean-based platform is developed using Unity3D. The employees are trained using the scaffolding erection case and the training performance is systematically evaluated. (4) The impact of the training programme, including the teamwork performance, is assessed through a comparative study of conventional VR based training and VR- and lean- based training. The detailed research methods are explained as follows.

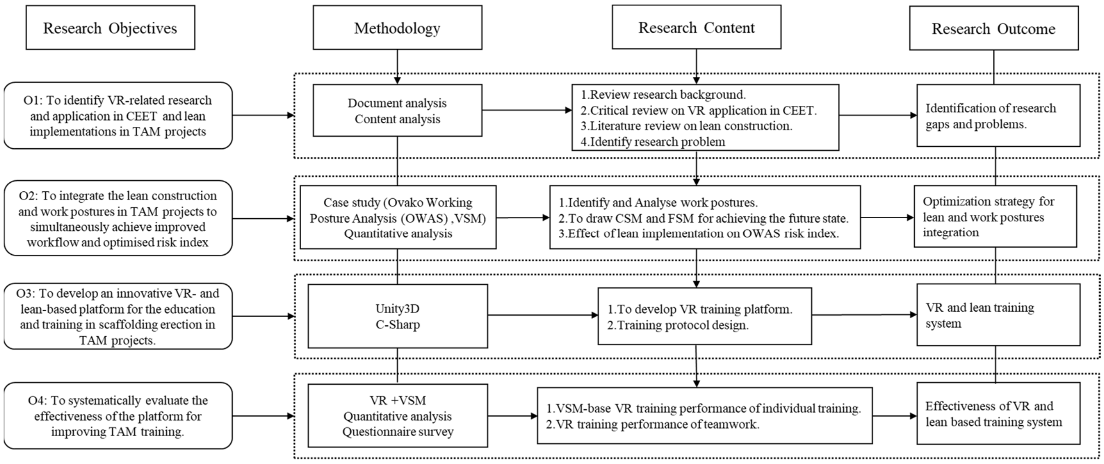


Figure 3-1: Research design

## 3.3 Research method for Objective 1

Objective 1 is to identify VR-related technologies and applications in construction engineering education and training (CEET), as well as lean implementation in the construction sector.

### 3.3.1 Data selection and analysis process for the use of VR in CEET

This review adopted a three-stage research design as shown in Figure 3-2. A paper retrieval process related to VR research and applications in CEET was conducted. All retrieved papers were then analysed based on the type of technologies implemented

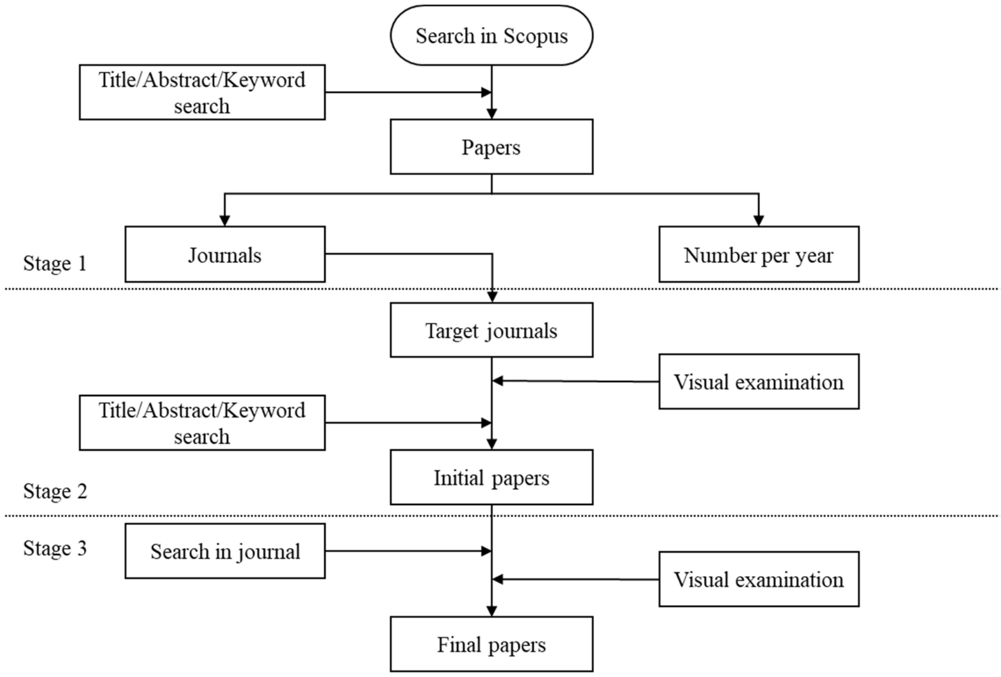


Figure 3-2: Three-stage Research Design

and the application areas. Results were summarized and future directions of VR research and applications in CEET were proposed.

- **Paper Retrieval:** Three search criteria are established for the paper retrieval process. As the systematic review is related to investigate VR-related research and applications in CEET, only academic journal articles are selected for review, considering their relatively high impact. Conference papers, book chapters and articles in non-leading or non-international journals were not considered. Scopus and Web of Science, which are the largest two academic databases, are used for the searching. In addition, the keywords used in the retrieval process included VR, virtual environment, 3D, game, construction, architecture, structural engineering education. The search rule is: (VR OR virtual environment OR augmented reality OR 3D OR game) AND (education OR training). All publications which contained the above keywords in the Title/Abstract/Keywords were identified. A total of 347 articles are retrieved from 1997 to September 2017. A manual screening process is then adopted to ensure all retrieved articles are related to the aim of this study. A total of 66 publications are identified for further analysis.
- **Data Analysis:** The 66 selected publications are analyzed based on a content analysis using a few codes. The codes are adapted from a few similar studies using content analysis, such as Mok et al. (2015). Table 3-1 shows the codes used in this study.

Table 3-1: Codes that are adopted for content analysis

| Codes | Descriptions of the codes |
|---|---|
| Publication year | The year of publication, from1997 to September 2017 |
| Author | List of authors in the selected publication |
| Publication venue | The journals which accommodate the selected publication |
| Country | The country where the selected publication is originated |
| Technology | The type of VR technologies that are adopted in the selected publication |
| Application | Categories of VR application in the selected publication |
| Future direction | Future studies stated in the article |

### 3.3.2 Data selection and analysis process for the evolution of lean construction research

- **Data Collection:** A three-step process was followed in order to systematically retrieve all bibliographic records on lean construction. The scope of the review was established at the beginning of retrieval process. Only journal articles and reviews were included due to their relatively high research impact. In addition, Web of Science (WoS), a premier research database, was adopted for the search. When the scope was identified, a searching process was initiated by using keywords "lean

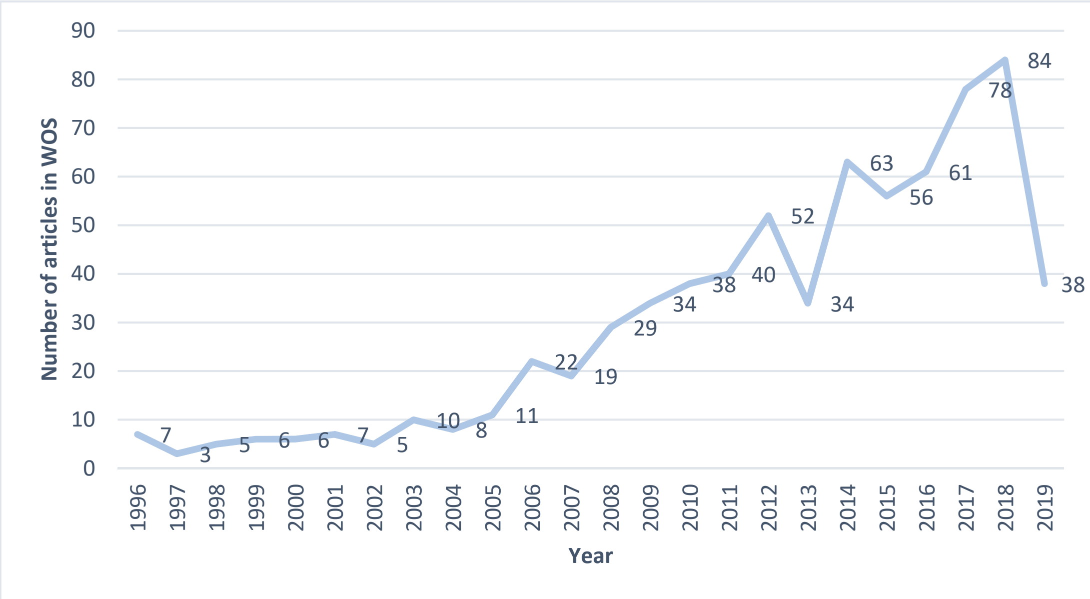


Figure 3-3: Number of publications on lean construction from 1996 to April of 2019

construction". All articles that included the keywords in the Title/Abstract/Keywords sections were identified. Finally, a manual examination was conducted to ensure all articles have relation to the development and application of lean construction. A total of 716 papers were selected for future analysis. Fig 3-3 shows the distribution of the 716 publications from 1996 to May of 2019. The number of publications has risen significantly since 2006, but dropped in 2013.

- Data Analysis: Bibliometric analysis is an information visualisation analysis tool that focus on citation analysis of publications to summarize the research achievements and seek development trends of a certain research domain (He et al., 2019). Domain analysis is bibliometric analysis of mapping the knowledge structure and revealing frontiers of development (Zhao et al., 2019). CiteSpace has a good capability in science mapping through visualising and analysing co-citation (Ruggeri et al., 2019). It can produce network mapping and visualisation through documents citations, the researcher can explore the implications hidden in a knowledge domain. Therefore, CiteSpace software was used to map the knowledge evolution of lean construction research, and determine main clusters in the knowledge map of lean construction. In this research, network of co-occurrence documents and network of keywords co-occurrence of bibliometric techniques were applied. The network of document co-citation can demonstrate underlying research speciality. It can be defined when two papers are cited together by another article, the more frequently the article cited by, the stronger their correlation. Documents co-citation analysis and citation bursts were used together for cluster analysis. For example, when an author or a group authors cite a specific article or a set number of articles, these citations may contain an idea or method that related to author's academic research, while these resources were received peer recognition. In CiteSpace, the account of citations to a reference can be identified. A node with a high citation burst normally refers that a potential research work has attracted great attention in a short period time. This bibliometric technique can detect the hot research topics and development frontiers in lean construction research, and also analyse the occurrence of changes in research trends of lean construction.

## 3.4 Research method for Objective 2

Objective 2 is to integrate the lean construction and work postures in TAM projects to simultaneously achieve improved workflow and optimised risk index. In order to better understand of the combined effect of lean and work postures on productivity improvement and health and safety in scaffolding erection, a case study approach as shown in Figure 3-4 was adopted in a typical LNG site where there was scaffolding erection work for LNG trains. According to Yin (2017), the method of case study is suitable when the investigator has little or no capability of controlling the

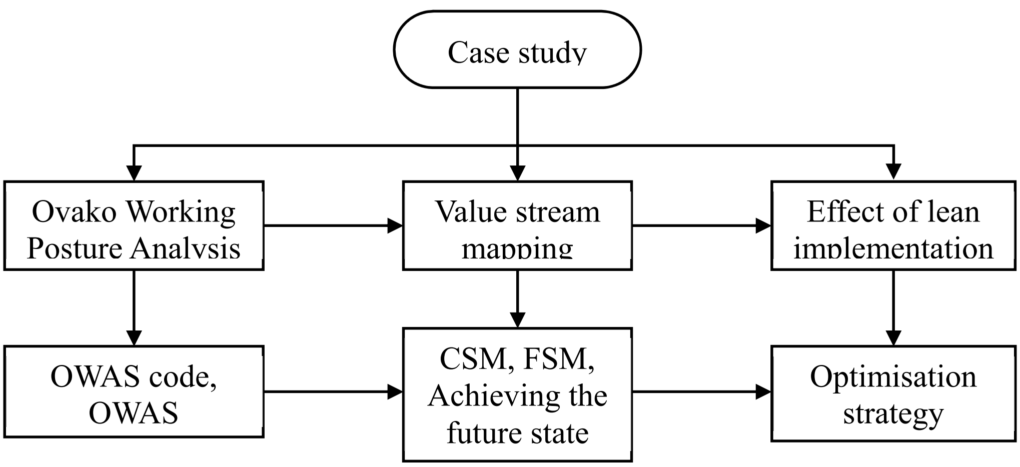


Figure 3-4: Research method of objective 2

event by examining an event in a real-life context. The case study was selected because of the importance of scaffolding erection to TAM in LNG projects. In addition, the scaffolding erection process is a repetitive process, meaning that the findings of the case study can be usefully generalized for other similar projects.

### 3.4.1 Case Description

The case study in this thesis was related to a TAM project in Dongara, Western Australia. The plant was completed and commissioned in 1998 at a cost of approximately $40M. Due to direct exposure, the pre-heater tower steelwork was deteriorating. Despite undergoing regular maintenance works, the plant steelwork was heavily corroded and major refurbishment was required. This study focused on the repairs on levels 5&6 of the pre-heater tower to return the structure to its as-constructed structural integrity. In this case study, scaffold erected on the construction site should be in good structural condition to achieve the project requirements. Also, this specialized work was necessary to ensure that the remaining maintenance activities can be completed on time and within budget.

### 3.4.2 Data collection

In order to systematically evaluate lean implementation in scaffolding operation, site observations, documentation and site interview with supervisors were conducted. By referring to the project schedule, an initial project process map was developed. The process map was then refined based on the data collected from site observations. Such data included manpower, value added time, processing time, waste time, waste category, and work postures of scaffolders.

To collect the postural data, four scaffolders who performed onsite scaffolding erection activities were recorded. The observation time was 1680 mins, which was the total processing time of scaffolding erection. The postural observations were made at 30 s intervals as proposed by the OWAS method (Kivi & Mattila, 1991). The observed operation activities consisted of the erection of scaffolding foundation, ground and first floor scaffolding, which were related to postures using back, arms, and legs for lifting. The observation lasted three days on site until the scaffolding in walkways and exclusion zones was completed. In order to analyse the data effectively, all working activities were videotaped at the construction site.

### 3.4.3 Data analysis

- VSM: VSM is a lean tool to eliminate waste and identify improvement areas. After gathering the data from site observations, processing time, value-added time, and waste time in each action were calculated. The four steps of VSM evaluation, as aforementioned, were followed. The identification of waste was supported by a focus group study with participants who have more than 10 years of working experience in TAM projects. In this study, 10 participants, including two schedule planners, two work package designers, one production manager, one site manager, one TAM superintendent, one maintenance vendor and two lean researchers were involved.
- OWAS: The risk index of working postures in each activity was also analysed with ErgoFellow software. This software has several ergonomic tools including OWAS to analyse and evaluate working posture for reducing occupational risk and productivity improvement. It is very useful for all professionals in the field of occupational health and safety (Dewangan & Singh, 2015). As mentioned in the literature review, four risk levels could be identified by the recorded onsite activities. Each working posture was represented by a numbered code. The numbered codes are explained as follows:
    - Four codes were used for activities that involved the use of back: 1 – straight; 2 – bent; 3 – twisted; and 4 - bent and twisted.
    - Three codes were used for activities that involved the use of arms: 1 - both arms below shoulder level; 2 - one arm at or above shoulder level; and 3 - both arms at or above shoulder level.
    - Seven codes were used for activities that involved the use of legs: 1 – sitting; 2 - standing on two straight legs; 3 - standing on one straight leg; 4 - standing or squatting on two bent legs; 5 - standing or squatting on one bent leg; 6 – kneeling; and 7 – walking.
    - Three codes were used for activities that involved the use of lifting force: 1 - less or equal to 10 Kg; 2 - greater than 10 Kg and less or equal to 20 Kg; and 3 - great than 20 Kg.

For example, an activity "Install the bracing in ground floor scaffolding" was numbered 1261, indicating that such activity involved the use of straight back, one arm at or above shoulder level, knelling and the use of lifting force less or equal to 10kg. Each activity was assigned to one of the four risk categories:

- Category 1 (C1): Working postures as regular and natural without harmful effects. There is no action required
- Category 2 (C2): Working postures have some potentially negative effects. Corrective actions will be required soon.
- Category 3 (C3): Working postures have a clearly hazardous effects. Corrective actions will be required as soon as possible.
- Category 4 (C4): Working postures have a very harmful effects. Immediate adjustment is required.

### 3.4.4 Optimisation strategy

In ideal scenarios, all waste can be eliminated to create a future state map. However, in real life projects, it should be noted that it is not common that all sources of waste can be eliminated and practitioners need to identify an optimized strategy to ensure that within the potential reduction target, e.g. a 10% improvement on processing time, maximum improvement in health and safety can be achieved. An optimisation strategy was therefore developed to ensure that minimum risk index can be achieved by eliminating waste following the VSM procedure. For the detailed processes related to the development of the optimisation method, please refer to Section 4.4.3.

## 3.5 Research method for Objective 3

### 3.5.1 The proposed training protocol

The research approach of objective 3 is to propose a new VR personalised training protocol for integrating lean concepts in training guidance. As shown in Fig. 3-5, trainees usually go through a task briefing and lecturing session to know the details of

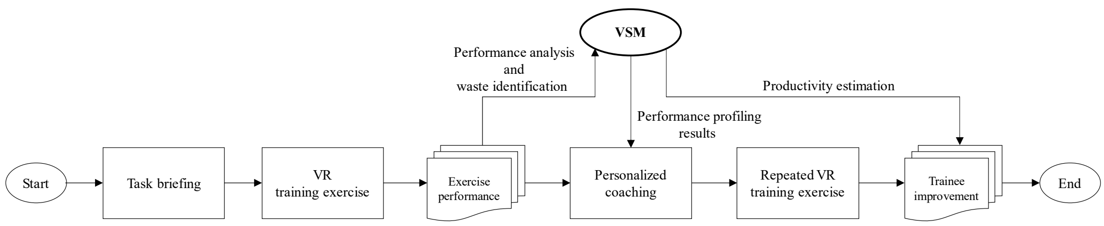


Figure 3-5: The proposed VSM-based VR personalised training process

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 the basic process for conventional VR training.

### 3.5.2 VR training scenario

The design of the virtual scaffolding erection scenario is shown in Fig. 3-6. 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. 3-6.

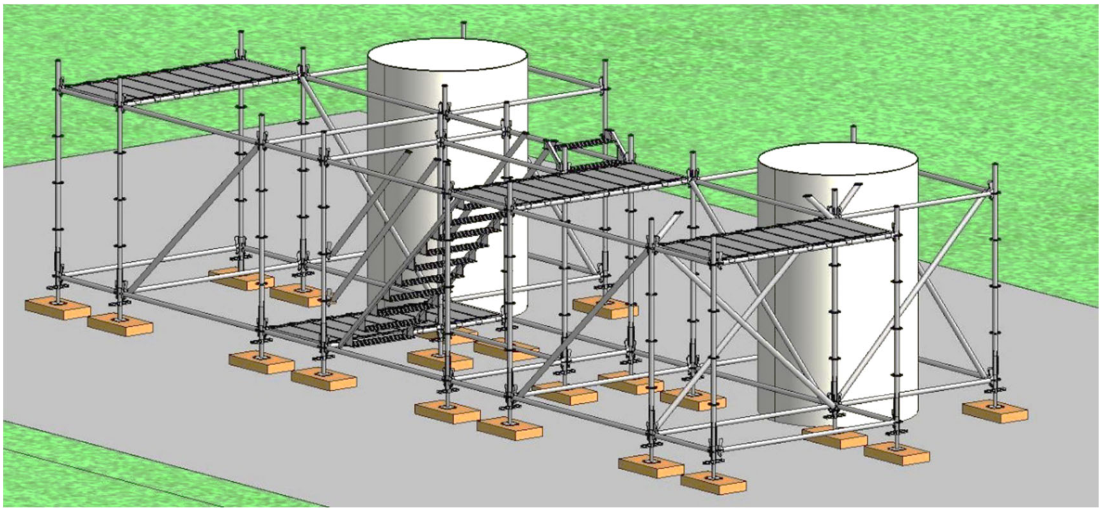

Figure 3-6: Overview of the virtual scaffolding erection scenario

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. 3-7. Detailed configurations of the hardware are provided in Table 3-2. 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 personalised guidance.

Table 3-2: 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 |

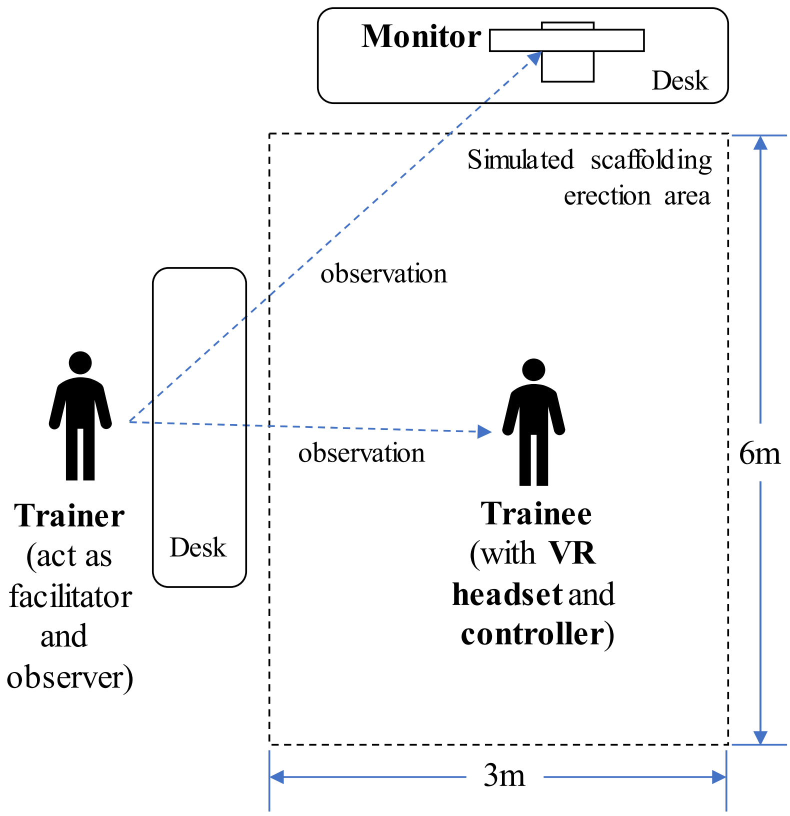


Figure 3-7: Environmental settings of the simulated scaffolding erection scenario

## 3.6 Research method for Objective 4

Objective 4 is to systematically evaluate the effectiveness of the platform for training improvement, as well as the effect of VR operational training exercise on teamwork skills.

### 3.6.1 Evaluation of VR- and lean-based training performance

The training performance of the new platform will be evaluated by 32 participants. The participants in the experiment were 32 male undergraduate students who had no experience related to VR operation and scaffolding construction. They were randomly assigned to two groups. Each group comprised of 16 students and they had to perform the scaffolding erection in the virtual environment using the VR equipment. To evaluate the performance of the designed training protocol, the before–after training experiment was conducted. The participants of Group 1 used traditional personalised training (video and lecture), whereas those in Group 2 used VSM-based personalised training to learn how to perform the scaffolding erection. To further validate the results of before-after training experiment, the effect size (32 participants) based on Cohen’s d benchmark (Cohen, 1988) was estimated for the justified validity of the t-tests. For detailed related to the participants’ details and size effect, please refer to Section 5.7.1 and Section 5.7.2, respectively.

In order to achieve the objective, 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 evaluations include comparing the significance in terms of time and error, assessing corresponding productivities, and evaluating trainees’ confidence in undertaking the individual training through a questionnaire survey. For the detailed calculations of time and error, please refer to Section 5.4

The Value-Added Time (VAT), Cycle Time (CT), number of errors, and Waste Time (WT) in each step were recorded; the Lead Time (LT) and Processing Time (PT) of the scaffolding processes were calculated for further productivity evaluation. The VAT is the processing time when the value-adding activities are performing during the scaffolding erection. CT is the frequency of scaffolding erection completion by every step. Number of errors is that the incorrect construction of each scaffolding components is recorded as one error, such as components misplaced with different dimensional requirements, picking up the wrong scaffolding components. WT is the time consumed by the trainee to perform the non-value-adding activity. The LT is the time consumed from the beginning to the end of the scaffolding. The PT is the duration between the start and finish time of the entire scaffolding erection process.

A t-test for identifying statistical significance was adopted to validate whether a significant difference of training performance exist for this new approach and the traditional VR approach. According to Johnson (1999), if $p < 0.05$, then their performances are significantly different; if $p \geq 0.05$, they are not. To further evaluate the overall training productivity, the productivity index [59] was calculated as follows:

$$P = (Q_a - Q_b)/(T_f - T_s)$$

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 personalised training with the traditional training, according to the qualitative results obtained from the trainees.

### 3.6.2 Evaluation of effect of VR collaborative training on teamwork skills

In order to understand the effect of VR operational training exercise on construction team work, this study is conducted by survey research method. As Gall et al. (2003) stated that the method of survey research is to use questionnaires for data collection and the results of data analysis can be generalized. The teamwork skills questionnaire was developed by O'Neil et al., (1997), which is used to measure teamwork skill that involves coordination, decision making, leadership, interpersonal skills, adaptability and communication. The questionnaires are shown in Appendix 1. The participants are requested to assign a rating from 1 to 5 (1: very poor; 5: very good) to each question. In order to validate if there is significant difference on construction teamwork competencies after VR operational training exercise, a paired samples t-test at 0.05 significance level is adopted.

## 3.7 Summary

This chapter describes the research methodology in this thesis.

First, a three-stage analysis is adopted for the review of VR technologies, applications and future directions. All bibliographic records on lean construction are also analysed through a systematic analysis. CiteSpace software is used to map the knowledge evolution of lean construction.

Second, a case study approach is adopted to integrate lean and work posture analysis in a scaffolding installation project in a TAM project. The lean improvement is conducted through VSM and the work posture analysis is conducted through the Ovako Working Posture Analysis System method. A three-step optimisation strategy is then developed for achieving optimized performance in waste reduction and work posture improvement.

Third, Unity3D is used to model virtual scaffolding operation scenario. The scaffolding components are created by Autodesk Revit 2018, exported in FBX format and imported the virtual scenario. A before-after experiment based on this virtual scenario is established.

Fourth, a variety of factors are used to evaluate the training performance of the new platform when compared with traditional VR training. T-test analysis is adopted for identifying statistical significance to evaluate if a significant difference occurred between the performances of conventional VR training group and VR- and lean- based training group.

# Chapter 4: Developing optimal scaffolding erection through the integration of lean and work posture analysis

The thesis in this chapter investigates the combined applicability of lean and work posture analysis in scaffolding erection and develops an optimized solution to achieve a balanced improvement on both productivity and health and safety of onsite workers. This chapter is organized in the following structure. Section 4.1 provides general introduction on lean maintenance and health and safety in construction operation. Section 4.2 presents work postures in construction operation. Section 4.3 presents the details of case study. Section 4.4 presents the results, including the current state map, future the state map and the optimized improvement strategy. Section 4.5 provides the discussion of this research and Section 4.6 summarises this chapter.

## 4.1 Introduction

Lean maintenance has been successfully used in the turnaround management to increase profitability and improve productivity (Anderson & Kovach, 2014; Mostafa et al., 2015). Instead of focusing on specific production or maintenance processes, the entire value stream of the process is mapped in lean (Rother & Shook, 2003). In addition, the lean method motivates employees as employee involvement is considered as one of the most important values in the lean concept. Lean techniques and tools, such as VSM, bring in a new way of helping identify customer values and eliminate non-value added activities (Zhang & Chen, 2016). By using VSM, Heravi and Firoozi (2017) investigated the production processes in prefabricated construction and found that VSM application is effective in time reduction and cost saving. In addition, Riddell (2017) examined how, when and where scaffolding should be utilized through lean in a construction project. It appears that lean provides useful value in turnaround maintenance and scaffolding erection.

However, it should be noted that health and safety in construction operation is always a critical issue in the LNG industry (Forte & Ruf, 2017). Health and safety issues such as ergonomic analysis of the construction workers has been recognised as a key contributor for improving productivity in construction industries (Kyaw-Myint et al., 2015) According to Occupational Safety and Health Administration (OSHA), about 2.3 million construction workers work on scaffolding regularly, and accidents related to scaffolding cause 4,500 injuries and $90 million in damage per year in US. Previous studies, which have adopted lean to improve TAM process, predominately use time and cost savings as performance indicators. For example, Kovach et al., (2014) demonstrated that lean method can help the project team reveal the underlying links of activities in each phase of maintenance project in order to identify value adding activities and waste. Kuhlang et al., (2011) developed the methods-time measurement (MTM) approach to reduce lead time and increase productivity. It is necessary to integrate health and safety considerations into the process so that a balanced improvement on productivity, as well as health and safety can be achieved.

## 4.2 Work postures in construction operation

As a high-risk field, the construction industry has very high rate of occupation disease (Vedder & Carey, 2005). Even though only 7% of work force are construction workers, construction activities cause more than 15% of all accidents among various industries in the European Union (Vedder & Carey, 2005). Comparative Performance Monitoring by Safe Work Australia reports (2017) that construction industry recorded the second highest incidence rate with 16.0 serious claims per 1,000 workers in Australia from 2015-2016. In addition, the work-related musculoskeletal disorders (WMSDs) account for about 34% of nonfatal injuries in construction industry, and construction workers are at about 50% higher risk to suffer from WMSDs than workers in other industries. According to OSHA, 9% of the fatalities in the construction industry each year are related to scaffold use, and scaffold-related activities account for 4,500 injuries and over 60 deaths every year.

Nowadays, LNG industry has focused on ensuring health and safety issues for construction workers, such as using ergonomic analysis to prevent injuries and fatalities during construction operation. For example, Cutlip et al., (2002) reduced overexertion hazards by optimizing hand location of scaffolder during scaffolding disassembly. Work posture assessment and heart rate elevations were also used to evaluate ergonomics in scaffolding construction by Saurin and Guimaraes (2006). It shows that lack of attention to ergonomics was identified as the root cause of the detected poor working conditions. Yuan and Buvens (2015) used Rapid Entire Body Assessment (REBA) method to evaluate the musculoskeletal injuries and disorders in scaffolding erection for construction companies. It shows that harmful work postures in scaffolding erection are caused by carrying heavy scaffolding materials, repetitive motions, reaching and holding overhead and kneeling on the scaffolding. In addition, REBA method has also been used to evaluate the movements of workers for process improvement during construction operation (S. Kim et al., 2011). However, the use REBA method requires an intermediate knowledge and understanding of biomechanics, which may be difficult for site managers. According to van der Beek et al. (2005), high risk of low back pain that caused by manual lifting in scaffolding operation needs to be prevented. The Ovako Working Posture Analysis System (OWAS) method (Saurin & de Macedo Guimarães, 2006) is a simple and systematic classification of work postures combined with observations to identify working postures, including four levels of the back, three levels of arms, seven levels of legs and three levels of the lifting force. This method uses a four-digit code to describe work postures. It can provide an easy risk classification and conduct extensive statistical analysis. The OWAS method has proven to be effective in practice in building construction to prevent ergonomic issue (Kivi et la., 1991). Lee and Han (2013) analysed working postures of construction workers using OWAS method in a dynamic construction site. The results indicate that bent and twisted trunk postures are the major risks to construction worker during the foundation construction. According to the OWAS method, worker's postures can be divided into four categories, including: 1. Working postures as regular and natural without harmful effects and there is no action required; 2. Working postures have some potentially negative effects and corrective actions will be required soon; 3. Working postures have a clearly hazardous effects and corrective actions will be required as soon as possible; 4. Working postures have a very harmful effects and an immediate adjustment is required. This method is therefore selected to evaluate work posture in scaffolding erection.

The integration of lean with other project requirements has been attracting increasing research attention. For example, Nahmens and Ikuma (2011) intended to integrate lean improvement with sustainability in modular homebuilding. Given the highest priority of productivity improvement and health and safety in TAM projects, there is a strong need to integrate lean and work posture analysis.

## 4.3 Case study

As the case description stated in Section 3.4.1, a total of 19 activities were identified in this case study as shown in Table 4-1. Figure 4-1 shows a simplified version of the scaffolding installation process the foundation work.

Table 4-1: Scaffolding Construction Activities

| Activities |
|---|
| Activity 1: Vertically line up with the corner of the structure in scaffolding foundation. |
| Activity 2: Layout the parts for scaffolding foundation. |
| Activity 3: Place the base plates for scaffolding foundation. |
| Activity 4: Adjustment for base plates of scaffolding foundation. |
| Activity 5: Install the base plates into standards. |
| Activity 6: Insert transoms and ledgers to standards. |
| Activity 7: Adjust the level of the bay in ground floor scaffolding. |
| Activity 8: Check the distance from the structure in ground floor scaffolding. |
| Activity 9: Adjustment for the bay of ground floor scaffolding. |
| Activity 10: Install the upper transoms and ledgers in ground floor scaffolding. |
| Activity 11: Install the bracing in ground floor scaffolding. |
| Activity 12: Lift the stair for ground floor scaffolding. |
| Activity 13: Place the planks for first scaffolding. |
| Activity 14: Install the standards to the existing standards in first floor scaffolding. |
| Activity 15: Install the transoms and ledgers. |
| Activity 16: Install the bracing for first floor scaffolding. |
| Activity 17: Lift the stairs for first floor scaffolding. |
| Activity 18: Add the toe boards and planks. |
| Activity 19: Hop up the brackets in first floor scaffolding. |

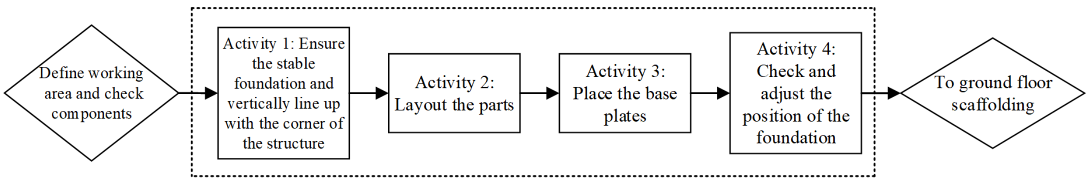


Figure 4-1: Scaffolding Foundation Construction Process

## 4.4 Results

VSM as lean tools is used to understand the integration of lean and work postures on productivity improvement and health and safety in scaffolding operation. Current state map (CSM), future state map (FSM) are analysed. The optimisation strategy is developed for achieving optimized performance in waste reduction and work posture improvement. The detailed results are stated as follows

### 4.4.1 VSM: Current state map

The current state map (CSM) of scaffolding erection of the foundation, ground floor and first-floor can be seen in Figures 4-2, 4-3 and 4-4 respectively. The indicators used to examine the effectiveness of the scaffolding operations in the VSM include two groups: the first group is related to operational efficiency including manpower, value added time, processing time, waste time and waste categories. The second group is related workers' postures, as an indicator for health and safety, including OWAS code and OWAS categories. In general, waste accounts for 508 mins, which is approximately 30% of the total processing time, which is 1,680 mins. In addition, the value adding time is 433 mins, which is approximately 25% of the total processing time, and non-value adding but necessary time is 739 mins.

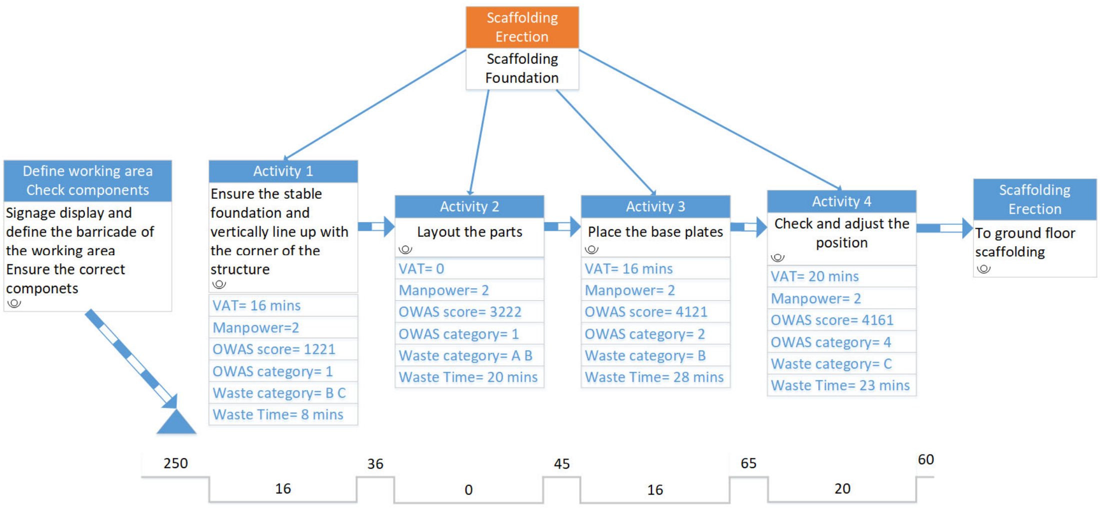

Figure 4-2: Current State Map – Scaffolding Foundation

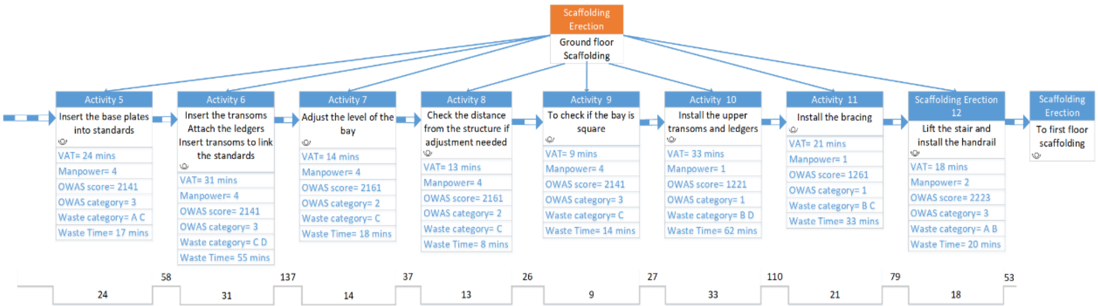


Figure 4-3: Current State Map-Ground-floor Scaffolding

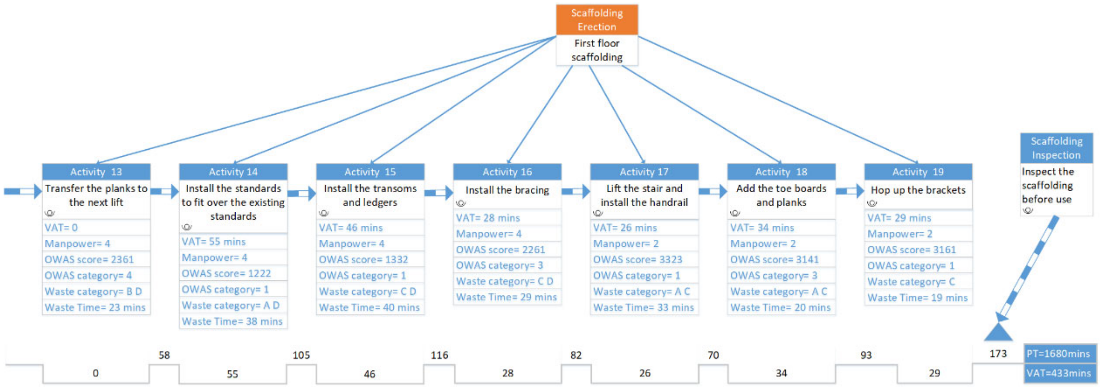


Figure 4-4: Current State Map-First-floor Scaffolding

The detailed analysis of waste activities in scaffolding erection are shown in Tables 4-2 and 4-3. As can be seen from Table 4-2, four general categories of waste, including unnecessary rework (category A), long travelling (category B), communication (category C) and waiting (category D) are observed. As can be seen from Table 4-2 and 4-3, the most significant waste category is communication, with a total value of 209 mins, about 40% of total waste time. This category of waste is mainly related to the communication between supervisors and scaffolders for working activities. For example, during the erection of first floor scaffolding, the supervisor took about 79 mins to explain the scaffolding planning to scaffolders. In addition, the second biggest waste category is waiting for materials to be delivered or the completion of the previous task, with a total value of 159 mins, which is about 31% of total waste time. For example, as scaffolding erection progresses to higher floors, the scaffolding components need to be transferred from construction site to first floor by workers and the scaffolders had to wait for the arrival. In addition, a detailed examination of the scaffolding erection of the foundation, ground and first floors also indicates that communication and waiting are the most significant waste sources, as shown in Table 4-3.

Table 4-2: Waste in scaffolding erection

| Waste category | Potential reasons | Waste time (minutes) |
|---|---|---|
| A Unnecessary Rework | Poor scaffolding operation planning | 68 |
| B Long Travelling | Locating and transferring scaffolding components | 72 |
| C Communication | Poor scaffolding operation planning | 209 |
| D Waiting | Transferring scaffolding components | 159 |
| | Total | 508 |

Table 4-3: Details of waste in scaffolding erection

| | Waste category | Waste reasons | Waste time (minutes) |
|---|---|---|---|
| Scaffolding foundation | A | Position of scaffolding parts cannot be accurately determined during the process. | 20 |
| | B | Some parts need to be transferred from scaffolding store area to foundation. | 16 |
| | C | Communicated work activities between supervisor and scaffolder. | 43 |
| | D | N/A | 0 |
| Ground floor scaffolding | A | The adjustment of stair position and few standards. | 17 |
| | B | Some parts need to be transferred from scaffolding store area to erection area. | 46 |
| | C | Communicated work activities between supervisor and scaffolder, communication about something not related to work. | 87 |

| | | | |
|---|---|---|---|
| | D | Waiting for Scaffolding parts delivery when install the ledgers, transoms and bracing. Previous step was incomplete. | 77 |
| First floor scaffolding | A | Few installation was not complete at one time due to higher location. | 31 |
| | B | Few parts need to be transferred from scaffolding store area to erection area. | 10 |
| | C | Communicated work activities between supervisor and scaffolder, communication about something not related to work. | 79 |
| | D | Waiting for Scaffolding parts delivery when install the ledgers, transoms and bracing. Previous step was incomplete. | 82 |

Table 4-4: OWAS code and category

| Activities | Initial OWAS code | Optimised OWAS code | Original OWAS category | Revised OWAS category |
|---|---|---|---|---|
| Activity 1: Vertically line up with the corner of the structure in scaffolding foundation. | 1221 | 1121 | 1 | 1 |
| Activity 2: Layout the parts for scaffolding foundation. | 3222 | 3122 | 1 | 1 |
| Activity 3: Place the base plates for scaffolding foundation. | 4121 | 2121 | 2 | 2 |
| Activity 4: Adjustment for base plates of scaffolding foundation. | 4161 | 2161 | 4 | 2 |
| Activity 5: Install the base plates into standards. | 2141 | 2141 | 3 | 3 |

| | | | | |
|---|---|---|---|---|
| Activity 6: Insert transoms and ledgers to standards. | 2141 | 2121 | 3 | 2 |
| Activity 7: Adjust the level of the bay in ground floor scaffolding. | 2161 | 2161 | 2 | 2 |
| Activity 8: Check the distance from the structure in ground floor scaffolding. | 2161 | 2161 | 2 | 2 |
| Activity 9: Adjustment for the bay of ground floor scaffolding. | 2141 | 2161 | 3 | 2 |
| Activity 10: Install the upper transoms and ledgers in ground floor scaffolding. | 1221 | 1221 | 1 | 1 |
| Activity 11: Install the bracing in ground floor scaffolding. | 1261 | 1261 | 1 | 1 |
| Activity 12: Lift the stair for ground floor scaffolding. | 2223 | 1323 | 3 | 1 |
| Activity 13: Place the planks for first scaffolding. | 2361 | 2341 | 4 | 3 |
| Activity 14: Install the standards to the existing standards in first floor scaffolding. | 1222 | 1222 | 1 | 1 |
| Activity 15: Install the transoms and ledgers. | 1322 | 1322 | 1 | 1 |
| Activity 16: Install the bracing for first floor scaffolding. | 2261 | 2261 | 3 | 3 |
| Activity 17: Lift the stairs for first floor scaffolding. | 3323 | 2323 | 1 | 1 |
| Activity 18: Add the toe boards and planks. | 3141 | 2121 | 3 | 2 |
| Activity 19: Hop up the brackets in first floor scaffolding. | 3161 | 3161 | 1 | 1 |

In addition, the initial assessment of the risk category of each activity is also provided in Figures 4-2, 4-3 and 4-4. Table 4-4 presents the result of the risk values of each activity. Figure 4-5 shows the distribution of working postures by OWAS categories in the scaffolding erection of each floor. Activities that have the highest risk value (category 4) account for 25% of scaffolding foundation construction. In addition, high risk value activities (category 3) account for 50% of ground-floor scaffolding erection. Adjustment to these activities need to be made as soon as possible. The high risk values are caused by bent and twisted back, as well as kneeling and bent legs. As can be seen from Figure 4-6, in terms of time, the back is bent and twisted for 53% of the time during scaffolding foundation construction. Figure 4-7 shows that in ground floor scaffolding erection, standing on two bent legs is considered as the most damaging position and accounts for 42% of the installation time. In addition, Figure 4-8 shows that, in first floor scaffolding erection, twisted back accounts for 38% of the installation time. Other damaging activities include arms are above shoulder level (42% of the installation time), and legs are kneeling (34% of the installation time).

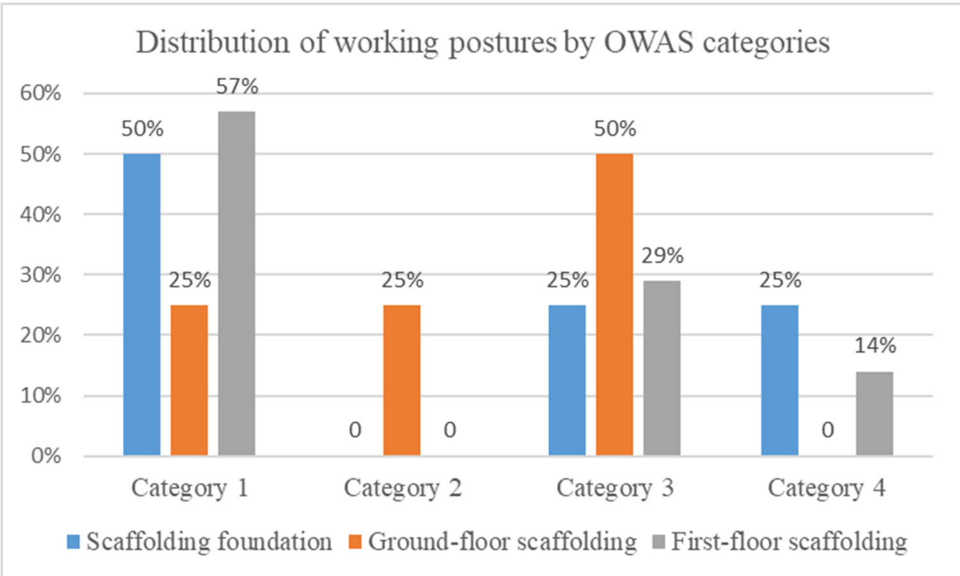


Figure 4-5: The distribution of working postures by OWAS categories

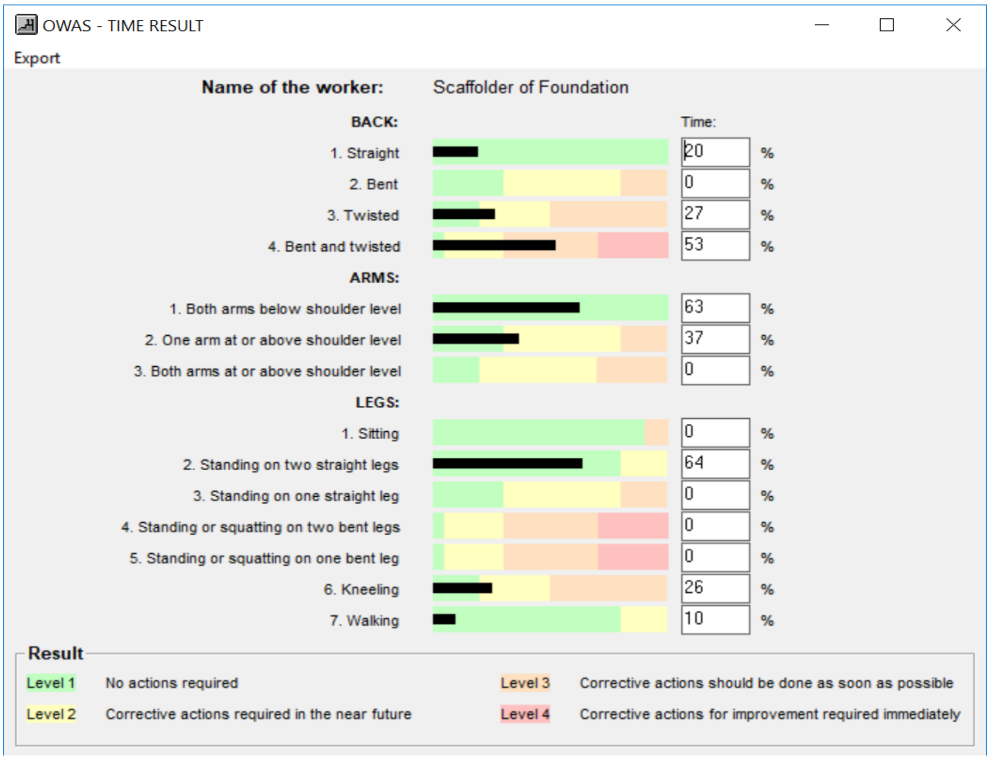


Figure 4-6: Working postures observed during scaffolding foundation construction

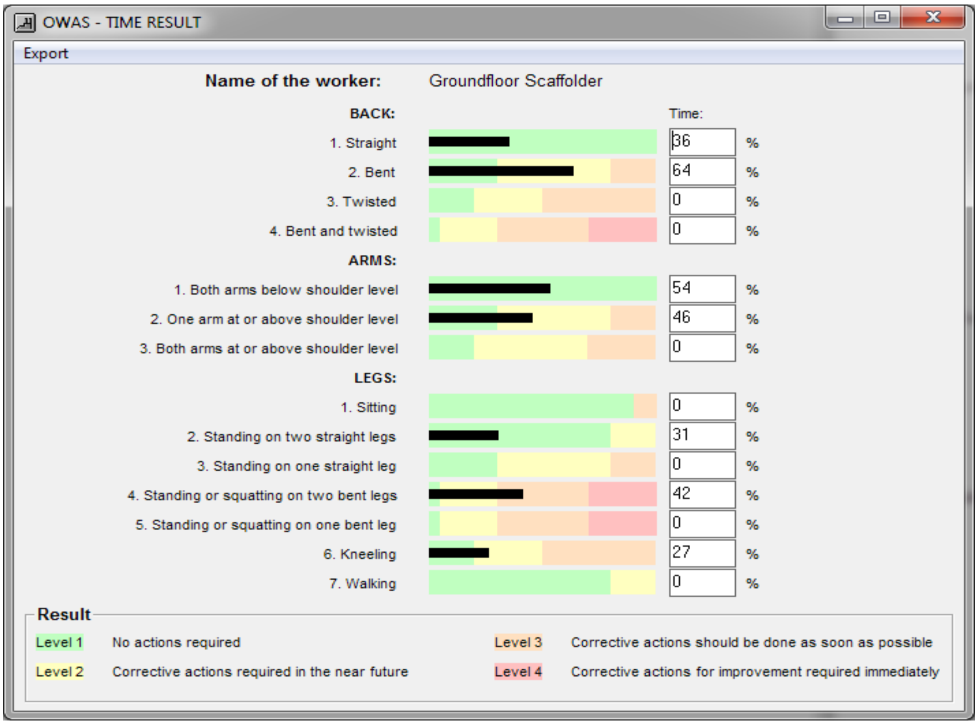


Figure 4-7: Working postures observed during ground-floor scaffolding construction

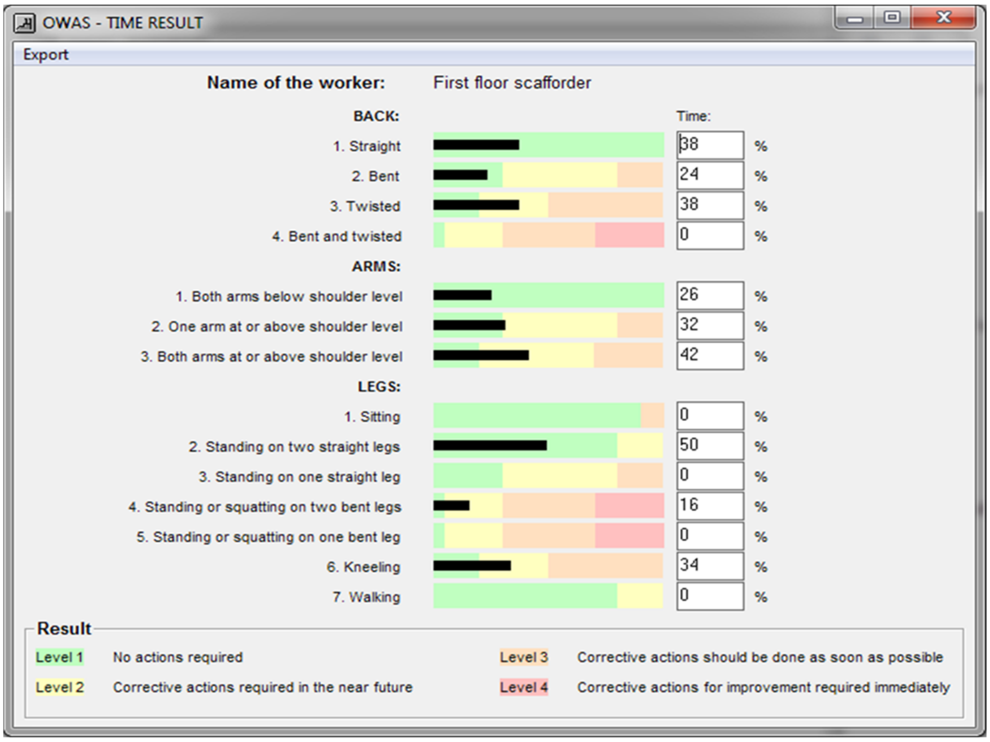


Figure 4-8: Working postures observed during first-floor scaffolding construction

After the determination of the risk value of each working posture, the overall OWAS risk index formula by Calvo (2009) was used to evaluate the overall risk level of the erection process. The equation for the calculation is:

$$R_P = \sum_{i=1}^{4} N_{C_i} C_i C_i / \sum_{i=1}^{4} N_{C_i} C_i \times 100 \qquad (1)$$

Where $R_P$the overall project risk index; $C_i(i = 1, \dots, 4)$ is the risk value of each OWAS category $C_1$, $C_2$ , $C_3$ and $C_4$ equal to 1, 2, 3, 4 respectively. $N_{C_i}$ is the total number of activities within OWAS category $C_i$.

When a waste time reduction strategy is applied, where the reduced waste time is $X$, then the risk index is calculated as:

$$\begin{cases} R_{P'} = \sum_{i=1}^{4} N_{C'_i} C'_i C'_i / \sum_{i=1}^{4} N_{C'_i} C'_i \times 100 \\ \sum_j T_j \geq X \end{cases} \qquad (2)$$

where $C'_i(i = 1, \dots, 4)$ is the risk value of OWAS category under a certain waste time reduction strategy, and $N_{C'_i}$ is the corresponding total number of activities within OWAS category $C'_i$, $R_{P'}$ is the risk index and $T_j(j = 1, \dots)$ is the total reduced waste time under this scaffolding erection combination scenario.

Based on Eq.1 and Table 4-4, the risk index of the original scaffolding erection is calculated as 265. According to Wahyudi et al. (2015), a risk value between 243 to

300 is considered to have considerable effect on workers and necessary mitigation activities should be conducted. In this project, it is therefore concluded that mitigation activities are needed to ensure the health and safety of onsite workers.

### 4.4.2 Future state map: an ideal scenario

The CSM provides a snapshot of the process of scaffolding erection and performance. It helps to identify the sources of waste and establish mitigation strategies. Figures 4-9, 4-10 and 4-11 represent the FSM when all sources of waste are eliminated.

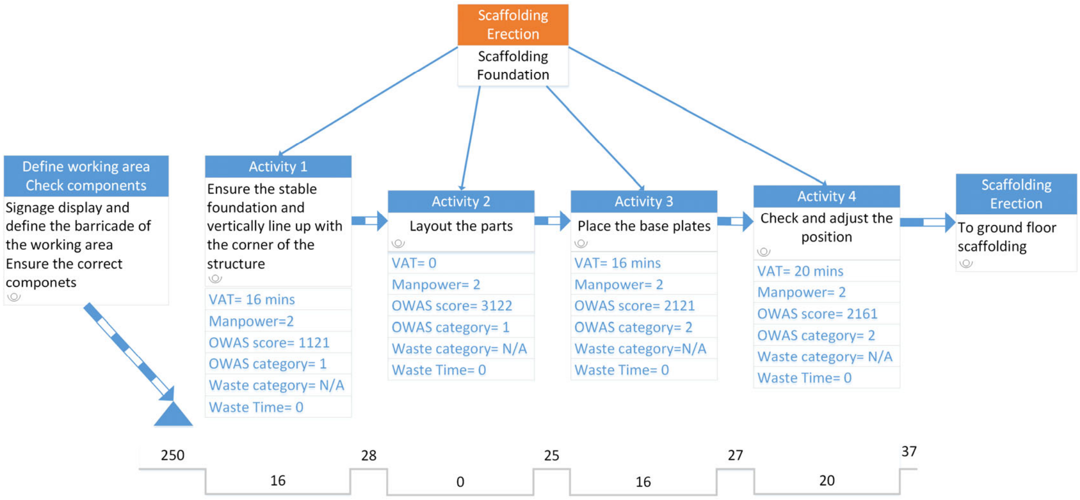


Figure 4-9: Future State Map – Scaffolding Foundation

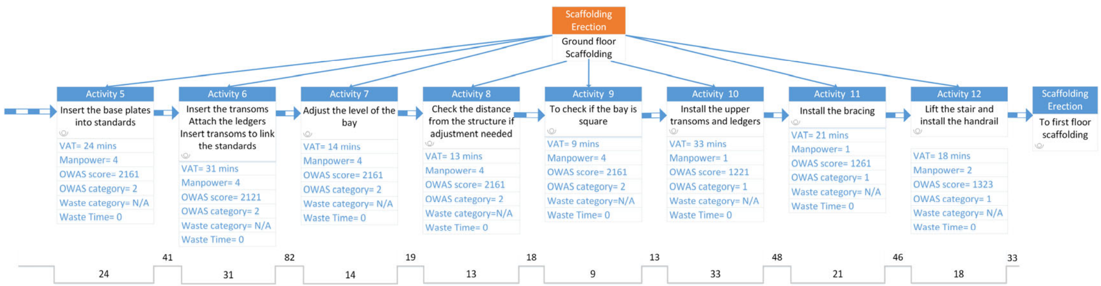

Figure 4-10: Future State Map – Ground-floor Scaffolding

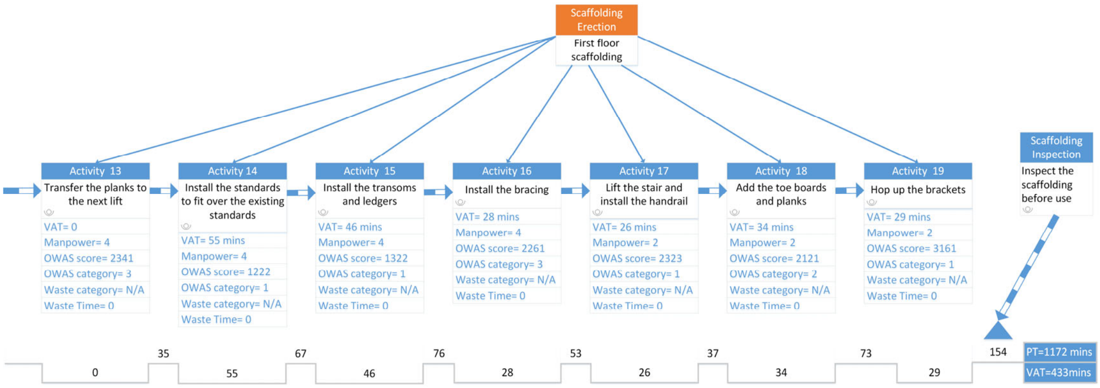


Figure 4-11: Future State Map – First-floor Scaffolding

Based on the sources of waste, potential improvements can be made in the following areas:

- Scaffolding parts could be placed as close to the location of use as possible to eliminate the unnecessary travel required to lift and deliver scaffolding components.
- The communication can be improved between the design department and supervisor to reduce reworks. For example, the problems that occurred on construction site should relay to the design department immediately.
- Site management should be improved for scaffolders to give details on how to solve problems in all aspects of the scaffolding construction being carried out. For example, an accurate scaffolding planning can be provided at the beginning of the work.
- Scaffolders need to be more systematically trained for lean construction.

Once all the sources of waste are eliminated, the processing time decreases from 1680 mins to 1172 mins, a 30% reduction. In addition, the percentage of value added time in scaffolding erection increases from 25% to 37%. The lead time of scaffolding foundation, ground-floor scaffolding and first-floor scaffolding are reduced by 38% (from 206 mins to 127 mins), 43% (from 527 mins to 300 mins) and 29% (from 697 mins to 495 mins) respectively. In addition, the improved risk value of the scaffolding erection process is 200.

### 4.4.3 Developing the optimized improvement strategy

An optimisation strategy was therefore developed to ensure that minimum risk index can be achieved by eliminating waste following the VSM procedure. The optimisation process is conducted through the below processes.

The first process in the optimisation is to determine the activities which can have an impact on the OWAS risk category once the waste within the activities is removed. As discussed earlier, postural observations were recorded at 30s intervals in a video clip. When waste is removed, postural observations associated with the waste activities will also be removed from the video clip. The revised video clip will then be analysed and the revised OWAS risk category of each activity can be obtained. The complete assessment of all 19 activities is shown in Table 4-4. It is found that only the removal of waste from six activities, including activities 4, 6, 19, 12 13 and 18 will have an impact on their OWAS risk categories. The six activities, their original risk categories and revised risk categories are also shown in Table 4-5.

Table 4-5: Waste time and variation in OWAS code and category

| Scaffolding erection activity | Initial OWAS code | Optimised OWAS code | Initial OWAS category（$P$） | Revised OWAS category（$P'$）if waste is removed | Waste time in activity (mins) |
|---|---|---|---|---|---|
| Activity 4 | 4161 | 2616 | 4 | 2 | 23 |
| Activity 6 | 2141 | 2121 | 3 | 2 | 55 |
| Activity 9 | 2141 | 2161 | 3 | 2 | 14 |
| Activity 12 | 2223 | 1323 | 3 | 1 | 20 |
| Activity 13 | 2361 | 2341 | 4 | 3 | 23 |
| Activity 18 | 3141 | 2121 | 3 | 2 | 20 |
| | | | | | Total 155 |

The second step in the optimisation is to determine the potential waste time removal interval. The OWAS risk categories are reanalysed by using OWAS method with Ergofellow software through video clip that all the waste is eliminated. Table 4-5 shows the waste time in the six activities, whose risk categories are changed once waste is removed. As only the removal of waste in these activities can cause a change of OWAS risk value, they are adopted to determine the waste removal interval. As can be seen from Table 4-5, the overall waste time which has a direct impact on the risk category is 155 mins.

The equation based on combinatorics of permutations theory (Bóna, 2016) used to identify the waste time removal intervals for this scaffolding process is:

$$I = f\left(\begin{array}{c}[0, x_{K(K=1,\ldots,n)},\ x_{K(K=1,\ldots,n)} + x_{L(L=1,\ldots,n,L\neq K)},\ x_{K(K=1,\ldots,n)} + x_{L(L=1,\ldots,n,L\neq K)} \\ + x_{M(M=1,\ldots,n,M\neq K,M\neq L)},\ x_{K(K=1,\ldots,n)} + x_{L(L=1,\ldots,n,L\neq K)} + x_{M(M=1,\ldots,n,M\neq K,M\neq L)} + \\ x_{N(N=1,\ldots,n,N\neq K,N\neq L,N\neq M)}, \cdots]\end{array}\right)$$

Where $I$ is the vector of waste time removal intervals, $f$ is sorting function; $x$ is the waste time in each activity; K, L, M, N, O, P… represent each activity in the construction process; $n$ is the number of activities. In this case, K, L, M, N, O, P represent activity 4,6,9,12,13 and 18 respectively, and $n$ is 6. The interval of reduced waste time is:

$$I = [0,14,20,23,34,37,40,43,46,54,55,57,60,66,69,75,77,78,79,80,86,89,92,98,100,109,112,115,118,121,132,135,141,155]$$

Based on the results, 28 intervals are identified, as can be seen from Table 4-6.

Table 4-6: Interval of reduced waste time

| No. | Interval of reduced waste time (mins) |
|---|---|
| 1 | $0 \leq T_1 < 14$ |
| 2 | $14 \leq T_2 < 20$ |
| 3 | $20 \leq T_3 < 23$ |
| 4 | $23 \leq T_4 < 34$ |
| 5 | $34 \leq T_5 < 37$ |
| 6 | $37 \leq T_6 < 40$ |
| 7 | $40 \leq T_7 < 43$ |
| 8 | $43 \leq T_8 < 46$ |
| 9 | $46 \leq T_9 < 54$ |
| 10 | $54 \leq T_{10} < 55$ |
| 11 | $55 \leq T_{11} < 57$ |
| 12 | $57 \leq T_{12} < 60$ |
| 13 | $60 \leq T_{13} < 63$ |
| 14 | $63 \leq T_{14} < 66$ |
| 15 | $66 \leq T_{15} < 77$ |
| 16 | $77 \leq T_{16} < 80$ |
| 17 | $80 \leq T_{17} < 86$ |

| | |
|---|---|
| 18 | $86 \leq T_{18} < 100$ |
| 19 | $100 \leq T_{19} < 109$ |
| 20 | $109 \leq T_{20} < 112$ |
| 21 | $112 \leq T_{21} < 115$ |
| 22 | $115 \leq T_{22} < 118$ |
| 23 | $118 \leq T_{23} < 121$ |
| 24 | $121 \leq T_{24} < 132$ |
| 25 | $132 \leq T_{25} < 135$ |
| 26 | $135 \leq T_{26} < 141$ |
| 27 | $141 \leq T_{27} < 155$ |
| 28 | $T_{28} \geq 155$ |

The final process is to identify the combination of activities in each waste removal interval and update the risk value of process once waste is removed. It should be noted that full removal of waste time in each activity is assumed, otherwise it would be impossible to identify the possible combination of activities in each waste removal interval. For example, in this project, the waste removal interval of [54, 55] can be achieved by removing waste in activity combination [9, 12 18] or activity [6]. When the combination is determined, the overall risk value is updated.

A total of 28 waste removal intervals is identified as shown in Table 3-5. The results, including the waste removal intervals, improved risk values and the best combinations of activities that can be eliminated to achieve the reduction target, are shown in Table 4-7. A few interesting findings can be obtained. The waste activities that have a direct impact on the overall process risk value account for 155 mins. When all these activities are removed, the minimum risk index that can be achieved is 200; a 24.5% improvement. With the additional elimination of waste in other activities, the risk index will not decrease, due to the reason that these activities do not include potentially harmful postures, such as bent back, kneeling and standing on one leg. Figure 4-12 shows the relationship between the reduced waste time and risk values of the process. It should be noted that, the overall risk value does not always reduce as reduced waste time increases, although a general declining trend can be observed.

Table 4-7: Result of minimum OWAS risk index in interval of reduced waste time

| No. | Interval of reduced waste time (mins) | OWAS Risk index | The best combinations of activities for reducing waste time | Other combinations of activities for reducing waste time |
|---|---|---|---|---|
| 1 | $0 \leq T_1 < 14$ | 265 | N/A | N/A |
| 2 | $14 \leq T_2 < 20$ | 258.97 | [9] | N/A |

| | | | | |
|---|---|---|---|---|
| 3 | $20 \leq T_3 < 23$ | 257.89 | [12] | [18] |
| 4 | $23 \leq T_4 < 34$ | 247.37 | [4] | [13] |
| 5 | $34 \leq T_5 < 37$ | 251.35 | [9, 12] | [9, 18] |
| 6 | $37 \leq T_6 < 40$ | 240.54 | [4,9] | [9, 13] |
| 7 | $40 \leq T_7 < 43$ | 251.35 | [12, 18] | N/A |
| 8 | $43 \leq T_8 < 46$ | 238.89 | [4, 12] | [4,18] [12, 13] [13, 18] |
| 9 | $46 \leq T_9 < 54$ | 235.14 | [4, 13] | N/A |
| 10 | $54 \leq T_{10} < 55$ | 244.44 | [9, 12,18] | N/A |
| 11 | $55 \leq T_{11} < 57$ | 258.97 | [6] | N/A |
| 12 | $57 \leq T_{12} < 60$ | 231.43 | [4, 9,12] [9, 12,13] | [4,9,18] [9, 13,18] |
| 13 | $60 \leq T_{13} < 63$ | 227.78 | [4, 9,13] | N/A |
| 14 | $63 \leq T_{14} < 66$ | 231.43 | [4,13,18] [12,13,18] | N/A |
| 15 | $66 \leq T_{15} < 77$ | 225.71 | [4,12,13] | [6,9] [6,12] [6,18] [4,13,18] |
| 16 | $77 \leq T_{16} < 80$ | 223.53 | [4, 9,12,18] [9, 12,13,18] | [4,6] [6,13] [6,9,12] |
| 17 | $80 \leq T_{17} < 86$ | 217.65 | [4, 9,12,13] [4, 9,13,18] | N/A |
| 18 | $86 \leq T_{18} < 100$ | 217.65 | [4, 12,13,18] | [6,9,18] [4,6,9] [6,9,13] [6,12,18] [4,6,12] [6,12,13] [4,6,18 ] [6,13,18] |
| 19 | $100 \leq T_{19} < 109$ | 209.09 | [4, 9,12,13,18] | [4,6,13] |
| 20 | $109 \leq T_{20} < 112$ | 237.14 | [6, 9,12,18] | N/A |
| 21 | $112 \leq T_{21} < 115$ | 223.53 | [4, 6,9,12] [6, 9,12,13] | [4, 6,9,18] [6, 9,13,18] |
| 22 | $115 \leq T_{22} < 118$ | 220 | [4, 6,9,13] | N/A |
| 23 | $118 \leq T_{23} < 121$ | 223.53 | [4,6,12,18] [6, 12,13,18] | N/A |
| 24 | $121 \leq T_{24} < 132$ | 217.65 | [4,6,12,13] | [4,6,13,18] |
| 25 | $132 \leq T_{25} < 135$ | 215.15 | [4, 6,9,12,18] [6,9,12,13,18] | N/A |
| 26 | $135 \leq T_{26} < 141$ | 209.09 | [4, 6,9,12,13] | [4, 6,9,13,18] |
| 27 | $141 \leq T_{27} < 155$ | 209.09 | [4, 6,12,13,18] | N/A |
| 28 | $T_{28} \geq 155$ | 200 | [4, 6,9,12,13,18] | N/A |

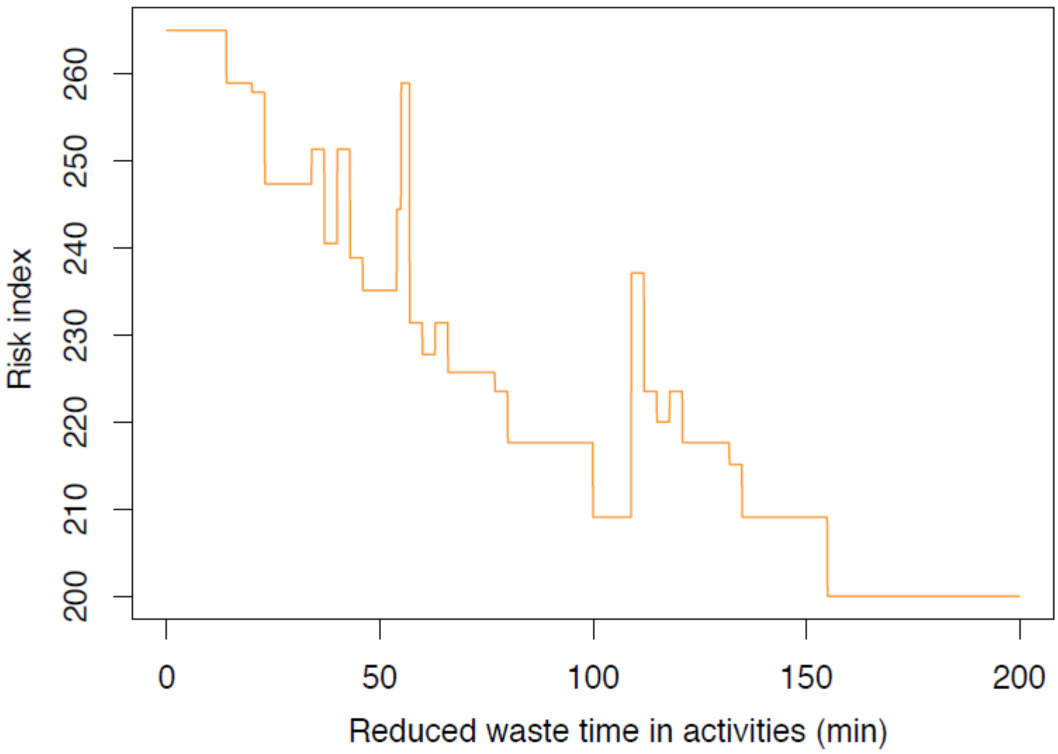


Figure 4-12: Risk index performance for reduced waste time in activities

## 4.5 Discussion

Lean philosophy has been rapidly recognized in the building and construction industry because it is believed to be effective in reducing operation waste and achieve improved productivity. Longoni et al., (2013) argued that most studies on lean considered the operational performance implications of lean and due to the importance of occupational health and safety, it is imperative to understand the occupational health and safety implications of lean implementations.

This chapter aims to investigate the waste and occupational health and safety issues in the scaffolding installation process in TAM projects. In accordance with Shou et al., (2015), it is found that waste, in terms of unnecessary rework, long travelling, communication and waiting, represent almost 30% of the overall processing time of scaffolding installation, indicating great potential for lean improvement. Such improvement is important because scaffolding installation and dismantling have significant impact on the tool operation, i.e. the physical engineering operation of TAM activities (Shou et al., 2019). In addition to the identification of waste, the case study also demonstrates that waste elimination not only affects scaffolding operation process improvement, but also the health and safety of onsite employees who are responsible for scaffolding installation. For example, eliminating unnecessary rework in stair lifting for scaffolding installation can reduce some safety hazards that could cause potential muscle strains and harmful work postures (Lee and Han 2013). In addition, such elimination can also reduce travel distance and decrease fatigue and tripping hazards. An optimized strategy exists for a preferred waste reduction target. However, it should be noted that although there is a general declining trend, i.e. as reduced waste time increases, the risk level declines, such trend is not linear. The reason is that some activities do not include potentially harmful postures. In addition, only full removal of waste in each activity is assumed. Therefore, at higher waste removal intervals, a completely different combination of activities may be needed. For example, in order to improve work efficiency by 37 minutes during the construction, the optimal combination of action is to eliminate the waste activities in A4 and A9, which the OWAS risk index is 240.54. For 55 mins, the optimal combination of action is A6, but 258.97 risk index is higher than 240.5.

The responses from industry participants on the results of this project were generally positive. All participants agreed that the classification of waste categories in terms of unnecessary rework, long travelling, waiting and communication is adequate. However, the interviewees also pointed out that such classification is based on the contractors' point of view. Other stakeholders, such as clients and suppliers, should also be involved. It should also be noted that interviewees suggested that the implementation of the approach can be improved by providing the guidelines for improving working conditions. The current approach considered the improvement in six activities as shown in Table 4-5. However, it does not mean that other activities do not incorporate harmful postures, even though these postures are not identified as waste activities.

## 4.6 Summary

Scaffolding construction is an important task in the LNG industry, considering the relatively low productivity, high labour shortage and cost in the process. Poor design, planning and scheduling of scaffolding often lead to issues such as idling, rework, unnecessarily long travelling time between activities, which substantially reduce productivity and pose health and safety risks. Given the higher priority of productivity improvement and health and safety in TAM projects, there is a strong need to integrate lean and work posture analysis. This c therefore aims to develop an integrated approach to improve productivity and health and safety in scaffolding erection by integrating work postures into the traditional VSM approach. The results show that waste activities account for 30% of the processing time of scaffolding installation. As for the relationship between reduced waste and improved health and safety performance, there is a general declining trend, i.e. as reduced waste time increases, the risk level declines, but such trend is not linear.

# Chapter 5: Adopting lean thinking in virtual reality-based personalised operation training using VSM

This chapter investigates how VSM, as a lean tool, can be applied to help improve operation training performances through an immersive VR-based personalised training programme. The specific objectives of this chapter are as follows: 1) to develop an immersive VR-based personalised 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 chapter is organized as follow. Section 5.1 is general introduction. Section 5.2 provides a review of lean concept for education. Section 5.3 provides a review of VSM for engineering education and training. Section 5.4 provides a review of virtual construction personalised training. Section 5.5 describes the proposed training protocol. Section 5.6 presents the experimental process for evaluating the performance of the training system. Section 5.7 presents the results. Section 5.8 presents the discussion, followed by summary being presented in Section 5.9.

## 5.1 Introduction

Lean principles have been successfully adopted in the architecture, engineering, & construction (AEC) fields to increase profitability and productivity (Anderson & Kovach, 2014). Lean techniques and tools, such as VSM, 5S, and just-in-time (JIT) offer new methods for identifying customer values and eliminate non-value-added activities (Zhang & Chen, 2016). Heravi and Firoozi (2017) 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 (Bayo-Moriones et al., 2010); Gratiela 2012). Ezema et al., (2017) reported that JIT provided better work motivation and operation in manufacturing plants. Anderson and Kovach (2014) 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., (2012) 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., (2018) 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 visualising 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) (Park et al., 2015; Clevenger et al., 2015), game technologies (Nikolic et al.; Li et al., 2012), and smart devices (Pedro et al., 2015) 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 (Park et al., 2015; Sampaio & Martins, 2014). Li et al., (2012) 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 programmes adopted traditional one-size-fits-all training methods that rarely consider the diversity of learning needs among individual trainees. According to Jeelani et al., (2016) better training performances can be personalised owing to the knowledge gaps and learning needs of individuals. Jeelani et al., (2017) stated that a more effective personalised training experience for construction workers can be provided through a virtual training environment.

## 5.2 Architecture of training protocols

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 (Ben-Daya et al., 2009). 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 personalised VR training is proposed herein and compared with conventional personalised 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. 5-1. 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 5.4 for more details). Subsequently, all trainees are randomly categorized into two groups. The first group focuses on conventional personalised guidance that provides instructions based on observations and trainee performances through the exercises. The second group is coached to provide instructions through VSM-based personalised guidance. The detailed procedure of the guiding process is detailed in Section 5.5. Subsequently, all trainees must reproduce the scaffolding erection operation under the same scenario. As discussed in Section 5.6, 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.

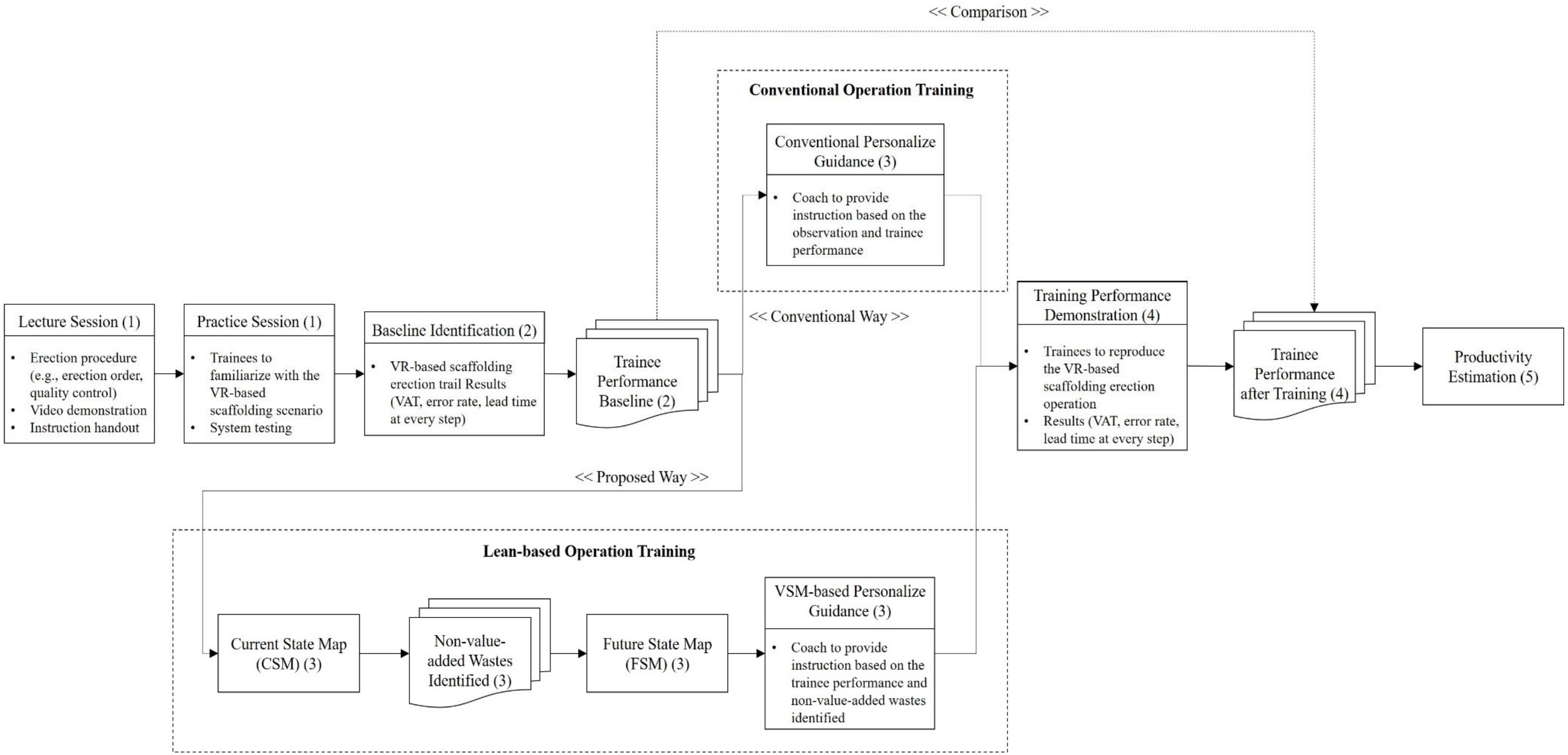


Figure 5-1：Architecture of training protocols under a before-after training scenario

## 5.3 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. 5-2. Moreover, the policy for safe scaffolding erection and use has been established (Beery 2002; Wang et al., 2020). 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

Figure 0-1: Architecture of training protocols under a before–after training scenario

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. 5-3. 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.

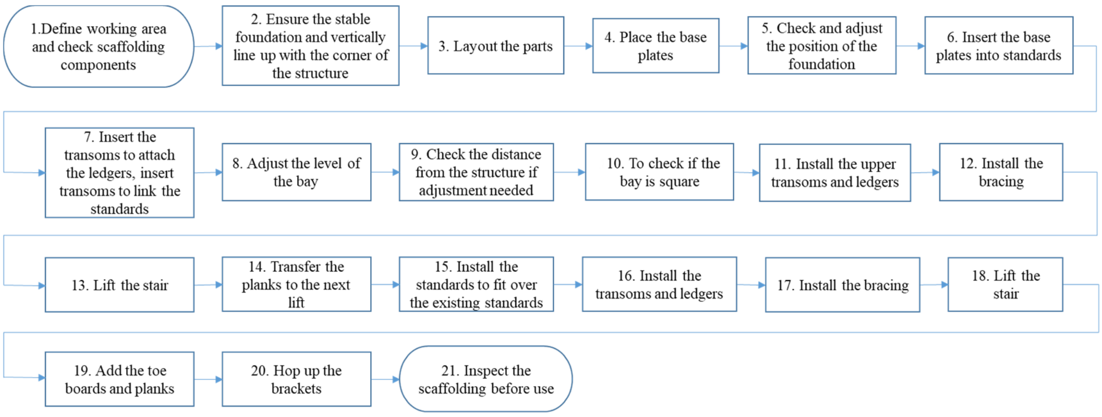


Figure 5-2: Scaffolding erection process

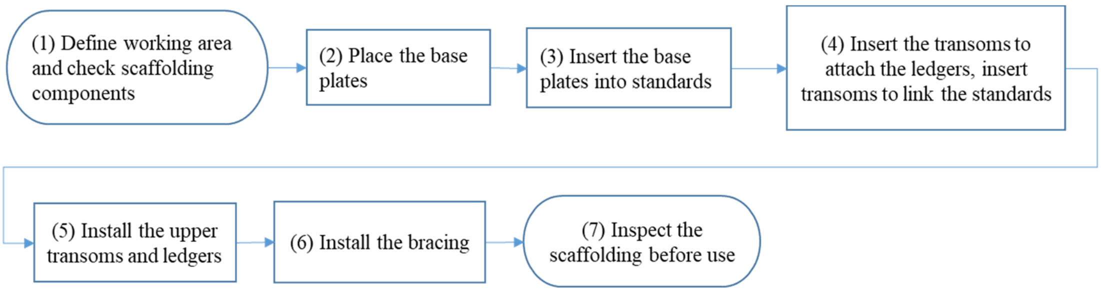


Figure 5-3: Steps selected for VR training experiments

To evaluate the potential benefits through the adoption of personalised 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 5-1.

Table 5-1: 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) (Rother & Shook, 2003) |
| Processing time (PT) | PT is the time consumed for scaffolding erection (specifically, steps 1 to 7 in Fig. 4) (Jeong & Yoon, 2016) |
| Value-added time (VAT) | VAT is the processing time associated with value-adding activities (e.g., actual installation work) during the scaffolding erection (Tyagi et al., 2015) |
| Cycle time (CT) | Frequency of scaffolding erection completion by every step (Barathwaj et al., 2017) |
| 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<br>B: Unnecessary traveling<br>C: Thinking (idling)<br>D: Rework |

## 5.4 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 (Earley et al., 1990). According to Hattie and Timperley (2007), 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 (Oseni et al., 2017) 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 the conventional VR training approach which relies on observation to provide guidance, the new training approach uses VSM to provide personalised guidance in Group 2. According to Rother and Shook (2003), 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 visualise 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.

## 5.5 Post-exercise and improvement evaluation

After Groups 1 and 2 have been trained through the conventional personalised and VSM-based personalised 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. 5-3, in which the trainees had to operate scaffolding components and place them at the correct positions.

## 5.6 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 personalised training (video and lecture), whereas those in Group 2 used VSM-based personalised 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.

### 5.6.1 Participants

The participants in the experiment were 32 male undergraduate students who had 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. All the trainees had to perform the scaffolding erection in the virtual environment using the VR equipment. As shown in Figure 5-4, all trainees had to perform the scaffolding erection in the virtual environment using the VR equipment.

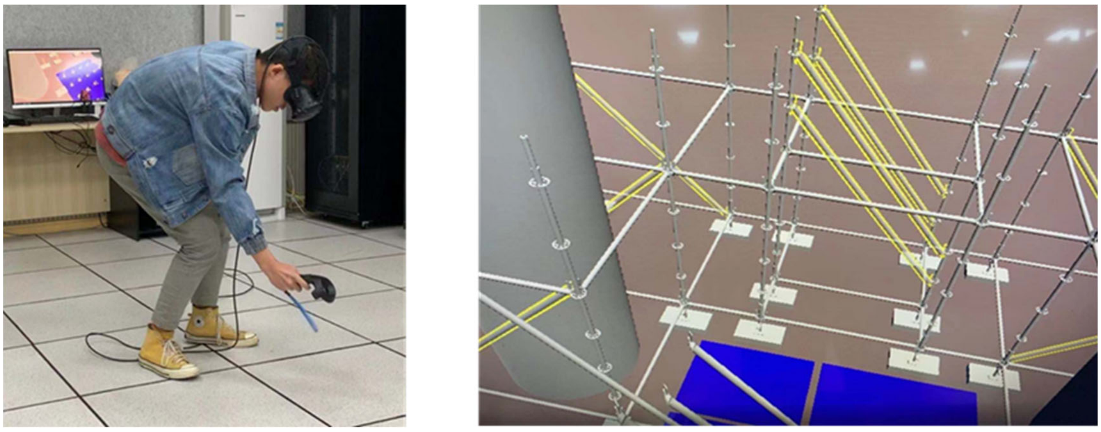

Figure 5-4: Example of simulated scaffolding erection operation in the virtual environment

### 5.6.2 Evaluation of the training performance

In order 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 personalised 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.

### 5.6.3 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 5-2. 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 5-2: 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 personalised training, and the before–after training performance of Group 2 is shown in Table 5-3. 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 5-3: 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. 5-5 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. 5-6, all sources of waste were expected to be eliminated adequately for the trainee's reference.

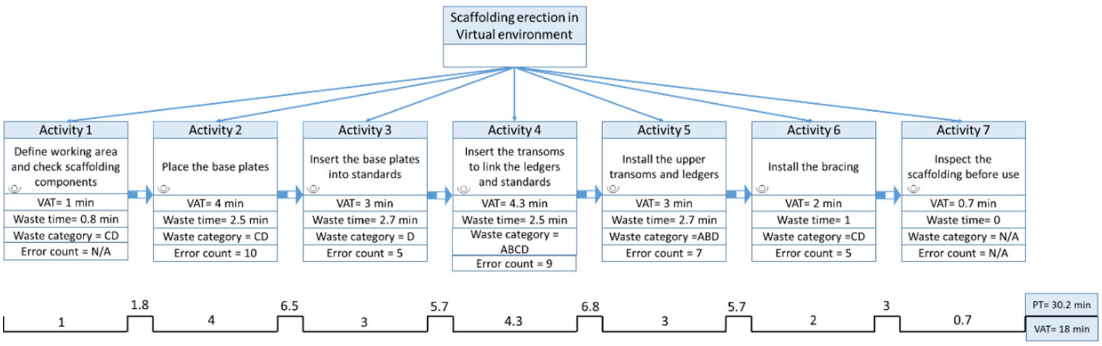

Figure 5-5: Example of CSM based on a trainee's performance in Group 2

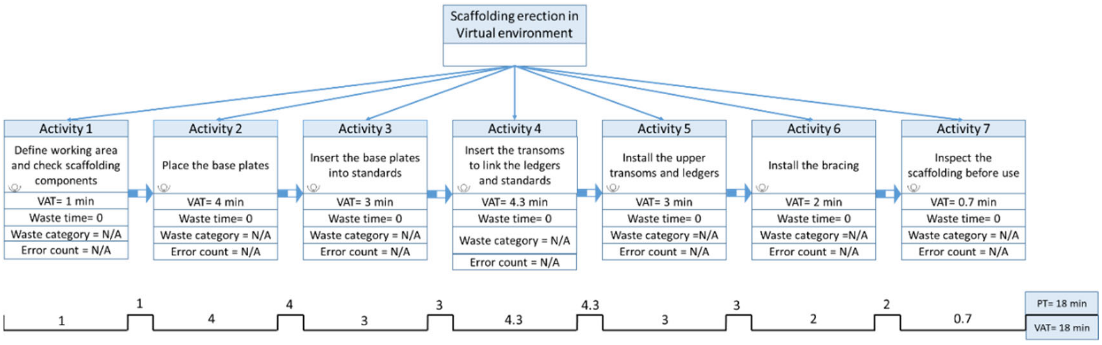

Figure 5-6: Example of ideal FSM based on a trainee's performance in Group 2

In terms of baseline adjustment, the result of the t-test before the training is as shown in Table 5-4. 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 5-4: Performance comparison before the personalised 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 personalised training approaches, the t-test is further conducted, as shown in Table 5-5. The VSM-based personalised training is significantly better than the conventional personalised training in terms of WT elimination (t=-4.066; p=4.72E-04<0.05), error reduction (t=-5.957; p=3.68E-06<0.05), and PT improvement (t=-3.945; p=5.08E-04<0.05). However, the VAT (t=-1.899, p=6.79E-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 (Cohen, 1988). 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 5-5: Performance improvement comparison after personalised 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 personalised training, the average performances of each indicator are presented. Fig. 5-7 shows the training effectiveness between conventional and VSM-based personalised 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.

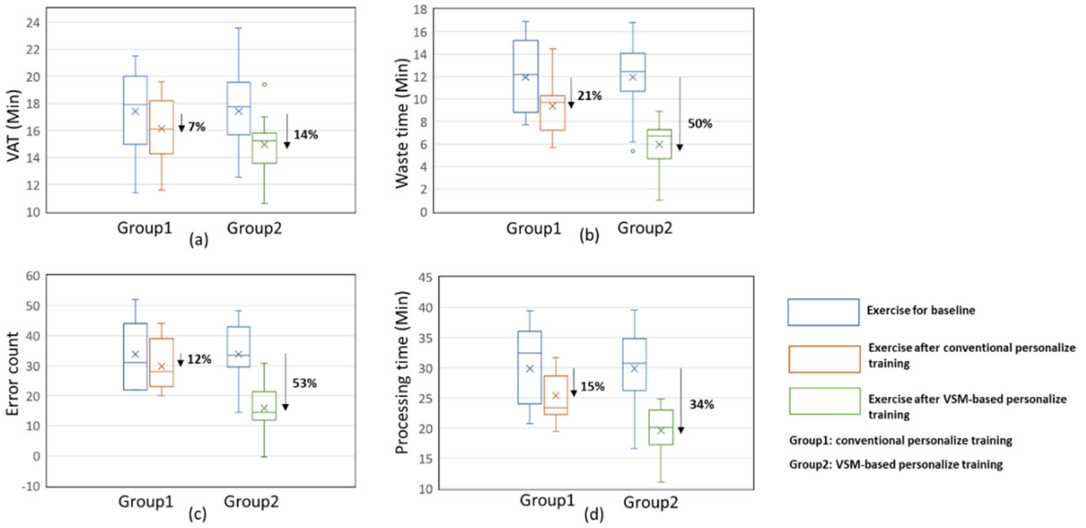


Figure 5-7: Comparison of conventional and VSM-based personalised training: (a) Value-added time; (b) Waste time; (c) Error count; and (d) Processing time

The training effects quantified by the VAT, as shown in Fig. 5-7 (a), indicate that the VAT can be reduced critically by the personalised 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. 5-7 (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 personalised training, the mean WT was now 5.95 mins, which is a 50% reduction. In other words, using VSM-based personalised training can reduce unnecessary travel, rework, and errors more effectively when compared with conventional personalised training.

The training effects quantified by the error count are shown in Fig. 5-7 (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 personalised 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. 5-7 (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 personalised training group, the mean PT was 19.6 mins, which was reduced by approximately 34% due to the overall error times and WT reduction.

### 5.6.4 Training productivity evaluation

An example of the productivity estimation can be seen in Table 5-6. It is based on one trainee's performance after he completed the personalised 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 is estimated to be 3.30.

Table 5-6: An example of trainee's productivity profile

| Exercise after the personalised 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 5-7 and 5-8 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 5-7: Productivity index of Group 1 after the conventional personalised 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 5-8: Productivity index of Group 2 after the VSM-based personalised 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 |

### 5.6.5 The trainees' confidence evaluation

All the trainees were instructed to complete the designed questionnaire, and the results are shown in Fig. 5-8. As shown, adopting the VSM-based personalised training over the conventional personalised 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).

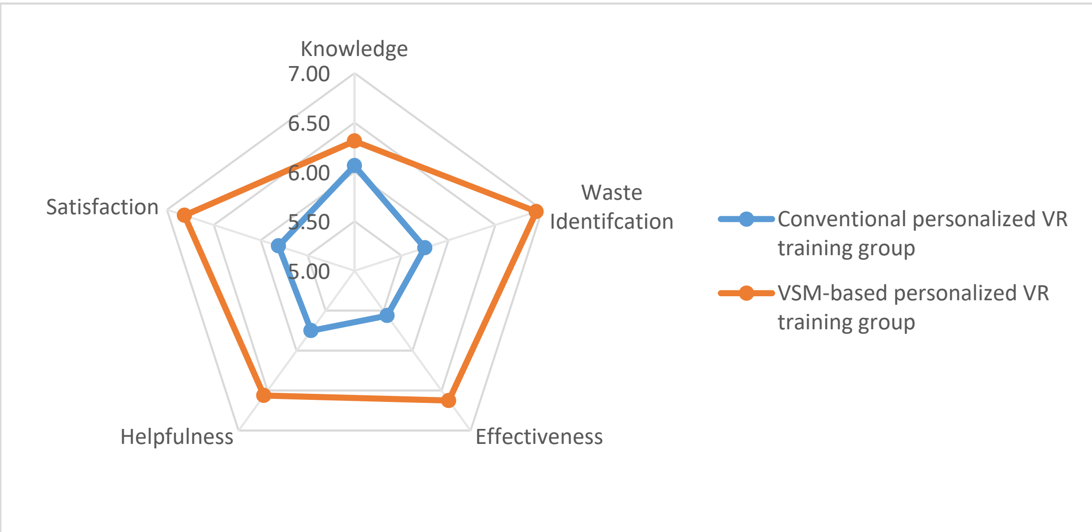


Figure 5-8: Comparison of mean values of training effects between the conventional VR training groups and VSM-based personalised VR training groups

## 5.7 Discussion

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

- As can be seen from Table 5-4 to 5-8, the improvement of VR-based personalised 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 personalised 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 personalised 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 5-7 and 5-8) 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. 5-6, 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 (Ahmad et al., 2018; Lobaugh 2008), 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. 5-7, 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 personalised 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 personalised 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 (Frank 2006). The struggles from trainees who were taught via the conventional approach could be caused by the personalised feedback information from the trainers, which was always diverged and sometimes more or less than required. According to LeMahieu et al.,

(2017), 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.

## 5.8 Summary

This chapter proposes the VR- and lean-based personalised training protocol, which includes: a lecture and practice session, the development of training baseline indicators, including value added time, number of errors, process time, and waste time, and a guiding session through conventional method and VSM. This proposed training protocol further introduces 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 personalised coaching; and 3) productivity estimation for identifying trainees' potential improvement.

VR scaffolding erection scenario, as an example, was conducted in this study to evaluate the training effectiveness between conventional VR and VSM-based VR personalised 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 personalised guidance demonstrated better productivity improvement than adopting the conventional personalised guidance. Furthermore, participants in conventional VR training demonstrated significantly higher error and WT reduction. Hence, VSM-based personalised 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.

# Chapter 6: Effect of VR collaborative training on teamwork skills

This chapter is to evaluate the effect of VR collaborative training on teamwork skills, including coordination, decision making, leadership, adaptability and communication. Teamwork skills are core skills in TAM projects and it is therefore necessary to investigate the performance of the new training platform on enhancing teamwork skills. This chapter is organized in the following structure. Section 6.1 provides general introduction on VR and construction teamwork. Section 6.2 presents teamwork skills for training collaboration. Section 6.3 presents VR for construction collaborative training. Section 6.4 presents the procedure of this experiment and participants. Section 6.5 provides the results and discussion of this research and Section 6.6 conclusion of this research.

## 6.1 Introduction

Due to the rapid evolvement from the technology at Architecture, Engineering & Construction (AEC) fields, providing sufficient training programmes to improve collaborative construction skills of employees has played an important role in the industry. As Zhao et al. (2015) pointed out, construction trainees are required to have certain non-technical competencies such as innovative, adaptive and collaborative. The trainees who gain experience from the construction collaborative and productivity training are more competitive in the workforce. According to a survey by the Society of Petroleum Engineers (2012), most participants stated that proper training is crucial to the development of employees. Both technical and non-technical training are the most important in the construction industry. Nowadays, it is also recognised that employers should not only hire employees but providing facilities and schemes for their further training and education (Ben-Daya et al., 2009).

Current training programmes in the construction industry are based on traditional methods, including on-the-job training and information-based training. Pennathur and Mital (2003) stated that training a workforce on-the-job could face possible damages due to the lack of experience. Also, practical training tasks should not influence the ongoing work, which may be difficult to achieve in on-the-job training (Gadre et al., 2011). Ariga et al. (2013) found that it is difficult to measure the effect of a training session on productivity and safety at the level of the individual trainee. Similarly, Jenkins et al. (2011) pointed out that information-based training, such as training with the aids of handbooks or lecturing with specific learning procedures is difficult to equip decision-makers with appropriate principals to cope with various situations. According to Ker et al. (2003), trainers play a vital role in a training session which could lead to different training outcomes based on their profiles and pedagogic levels. Most of the construction training courses are conducted in a classroom. Examples and video clips of past construction projects are used to aid the learning and understanding of the construction process. Although video learning could assist trainees in visualising construction tasks and activities, trainees cannot interact with the videos.

VR is believed to be effective in improving the quality of construction engineering training and education programmes (Wang et al., 2018). Comparing with the training approaches mentioned above, VR-enabled training provides an efficient environment for trainees to rehearse their operations without limitations of time, constraints of physical presentations, and potential high expenses on setting up the environment. Studies confirmed that VR training system can be used to create effective training activities for the construction industry. VR training also stimulates learning and promotes trainee interaction. However, current VR-based training studies in the construction industry tend to focus more on improving the individual training experience (Du et al., 2017). It is controversial to the situation at operation sites where workers' collaboration carries out most of the construction or maintenance tasks. Despite some researchers have developed VR training systems on collaborative tasks for multiuser in recent years, they seldom discuss what would be the problems of the collaborative training through traditional training such as video and lecture based training. Also, there is a lack of studies on how VR collaborative training strategies can be evaluated and improved with productivity concerns. Li et al. (2012) developed a multiuser virtual safety training system for tower crane dismantlement to enhance trainees' practical knowledge. Vahdatikhaki et al., (2019) proposed a framework to integrate actual construction project data into a VR training system for multiple trainees to enhance construction safety and teamwork. These studies focus on the isolated application of VR to address a specific training need. The concerns of considering how to improve workforce collaborative competencies and behavior through training are not addressed here.

## 6.2 Teamwork skills for training collaboration

A team is composed of individuals, as two or more people working together to accomplish a common task or achieve a shared goal (Cohen & Bailey, 1997). Individuals in team should cooperate and dynamically adjust their efforts according to the dynamic performance of other team members to achieve this goal (Rosen et al., 2010). The outcome of teamwork must consider not only the final results of the task, but how the individuals achieve the results. O'Neil et al., (1997) stated that individuals of an effective team need to be prepared for tasks in teamwork and should know how to coordinate team activities, communicate effectively with other team members and respond to changing conditions in team process. O'Neil et al., (1997) identified six teamwork competencies that are necessary to the effective team:

- Adaptability is a process by which the team members can detect the problems and adjust teamwork strategies according to the information gained from teamwork process (van der Beek & Schraagen, 2015). According to O'Neil et al., (1995), the important aspect of adaptability in teamwork process is the ability to recognize and remedy the problem.
- Coordination is a process by which integrated team activities, knowledge, and responses to complete a task (Kuehl, 2001). High level of team coordination will accomplish a task with integration, synchronisation and completion and all the team members' work will contribute to the results (Chung et al., 1999).
- Decision-making is the ability to capitalize on available information to identify possible alternatives, select the best solution and to help team members evaluate the consequences (Chung et al., 1999).
- Interpersonal is the skill that can enhance interaction and conflict of team member using cooperative behaviours (O'Neil et al., 1997). Team performance is highly dependent on interpersonal skill of individual team member (Page and Donelan, 2003)
- Leadership is the ability to coordinate and supervise the team member activities, plan and organise the team task (O'Neil et al., 1997). Leadership should include proper alignment of team member, and motivate the team members as they produce useful and innovative changes to complete the task (Crawford et al., 2000).

- Communication is ability to accurate information exchange between team members (Kuehl, 2001). As stated by O'Neil et al., (1997) the effective communication integrates expectations of team member, activities, response and feedback behaviors.

## 6.3 VR for construction worker's collaborative training

The use of VR to enhance the capacity of construction operation has been implemented in the field of construction engineering. The immersion and interaction of VR enable trainees to play a role in the virtual learning environment and devote themselves to the learning environment, which is very beneficial to trainees' operational skills training. Because the VR training environment is not in any unsafety situation, students can practice repeatedly until they master the operational skills. For example, Langley et al., (2016) established the virtual training system for assembly operations within the automotive industry. The objective and subjective methods were used to investigate training performance. It shows that VR training is effective in avoiding error during the task when compared with conventional training processes. Hou et al., (2017) proposed a framework to improve the process of complex procedural skills in oil and gas facilities. The results reveal that the VR training system clearly promotes workforce productivity while bringing down rework. Additional, some researches proposed VR integrated with management theroies such as process mining (Roldán et al., 2019) and lean management (Kayumi, 2013) to enhance the training effectiveness and performance of industrial operators. However, most of VR-based operation training system can only provide single-person interaction scenarios, which means that only one person can participate in the virtual environment.

Construction workers' collaboration is important to any construction project. The effective collaboration of construction worker can ensure the construction quality and complete the project on time with the budget (Mitropoulos & Memarian, 2012). Therefore, the cooperation of the construction workers in the team directly affects the efficiency of the project and leads to lots of benefits, such as saving time and cost, reducing unnecessary rework and operational errors during the construction process. The efforts of coordination and cooperation are essential for productivity improvement in the construction industry. Collaborative training can not only enable trainees to learn the spirit of respecting others, but facilitate trainees' performance (Sung & Hwang, 2013). According to the examination by Hummel et al. (2011), the collaborative training method significantly improved the quality of the learning outcomes. In addition, technologies such as VR have significantly impacted on facilitating collaboration for workers over the last ten years. Collaborative VR of training is one of the important factors to facilitate construction training effectiveness (Le et al., 2015), which can provide virtual 3D content that enables participant to interact with each other. For example, a cloud-based multi-user VR system was proposed by Du et al. (2017), it demonstrates that the VR collaborative training system can improve interpersonal interaction and communication in a construction project. Shi et al. (2016) developed a BIM-based VR multi-user platform for facility management to facilitate collaborative maintenance operation, it shows that the proposed system can assist the trainees to improve maintenance efficiency. Although studies pointed out that the adoption of VR technology has a positive impact on collaborative training in the construction industry, there are still lacking from a comparative perspective that involved specific cooperative construction task for collaborative evaluation (Lorenzo et al., 2012). Neither, the effect of VR multi-user training on teamwork skills is still underdetermined.

## 6.4 Experiment procedure and participants

Figure 6-1 shows the evaluation process of the effect of VR operational training exercise on teamwork. All participants are required to complete the questionnaires related to teamwork skill competencies. Then they go through a collaborative task briefing to understand the details of the VR collaborative operation task. The setting of the VR training scenario and relevant tasks are described in Section 3.5 and Section 5.3, respectively. Afterward, the participants need to complete the VR scaffolding erection in pairs. In the process of collaborative task completion, there is no requirement for the participants to complete the task, but the participant needs to experience teamwork through virtual operation. Finally, all participants are required again to complete the same questionnaires to evaluate the effect of VR operational training exercise on teamwork skills.

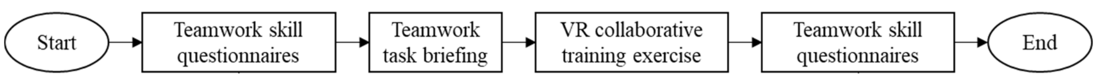


Figure 6-1: The evaluation process of VR operational training exercise on teamwork skill

The participants in this experiment are 36 male undergraduate students who had no experience related to VR operation, but they all had teamwork experience. They are from the School of Engineering and Technology at Southwest University, China. The average age of them is 22.4 years old, with a rage of 21 to 23. The 36 participants are randomly divided into 18 groups, two students are in a group as shown in Figure 6-2.

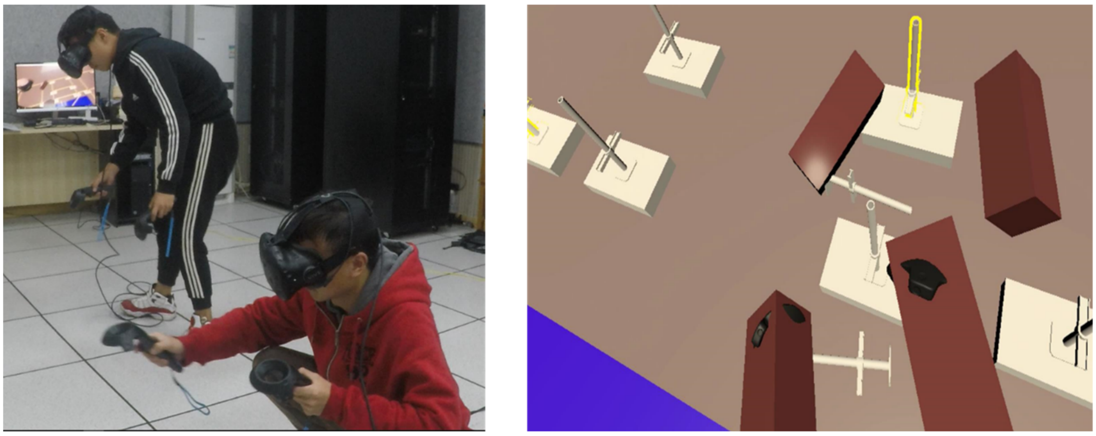

Figure 6-2: Example of simulated collaborative scaffolding erection operation in the virtual environment.

## 6.5 Results and discussions

The experiment results, including the before-after teamwork skills performance, the average score of coordination, decision making, leadership, interpersonal skill, adaptability and commutation were collected. The radar chart (Figure 6-3) illustrates the average values of teamwork skills in coordination, decision making, leadership, interpersonal, adaptability, and communication. Table 6-1 shows the details of teamwork skills scores. The average coordination scores before and after the training were 2.58 and 2.31, respectively; the average decision making scores were 2.66 and 2.87, respectively; the average leadership scores were 2.57 and 2.69, respectively; the average interpersonal skill scores were 3.22 and 3.35, respectively; the average adaptability scores were 2.63 and 3.24, respectively; the average communication scores were 2.90 and 3.11, respectively;

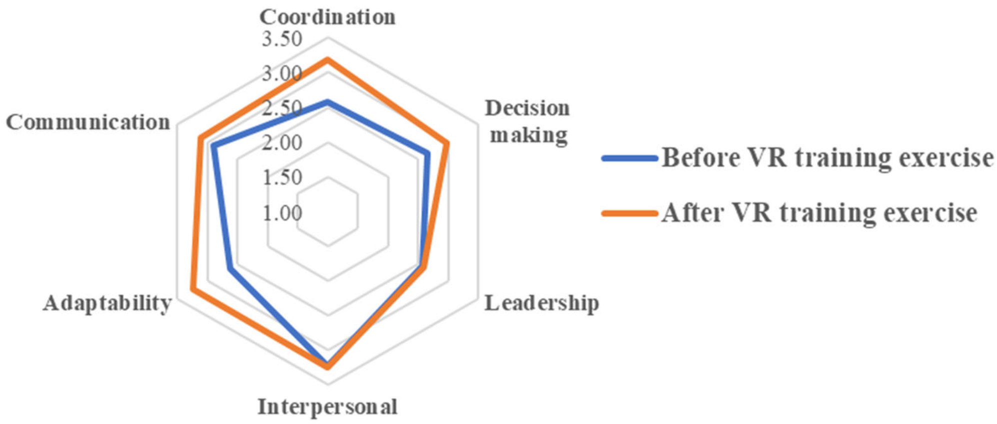


Figure 6-3: Average values of the questionnaire in teamwork skills

Table 6-1: The teamwork skills questionnaires score

| | Coordination | | Decision making | | Leadership | | Interpersonal | | Adaptability | | Communication | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trainee No. | Before VR exercise | After VR exercise | Before VR exercise | After VR exercise | Before VR exercise | After VR exercise | Before VR exercise | After VR exercise | Before VR exercise | After VR exercise | Before VR exercise | After VR exercise |
| 1 | 2.50 | 3.25 | 2.50 | 3.00 | 2.25 | 2.25 | 3.00 | 3.00 | 2.25 | 2.75 | 2.75 | 3.00 |
| 2 | 3.25 | 3.50 | 3.75 | 3.75 | 3.75 | 3.75 | 3.50 | 3.50 | 3.75 | 3.75 | 3.50 | 3.50 |
| 3 | 2.75 | 3.50 | 2.75 | 3.00 | 2.00 | 2.25 | 3.00 | 3.00 | 2.75 | 3.25 | 3.00 | 3.00 |
| 4 | 3.25 | 3.50 | 2.75 | 3.25 | 3.00 | 3.00 | 3.75 | 3.75 | 3.00 | 3.25 | 3.50 | 3.50 |
| 5 | 2.75 | 3.25 | 3.00 | 3.25 | 2.00 | 2.00 | 3.75 | 3.75 | 2.25 | 3.00 | 3.50 | 3.50 |
| 6 | 2.75 | 3.25 | 3.00 | 3.00 | 2.75 | 2.75 | 3.00 | 3.00 | 2.75 | 3.00 | 2.75 | 2.75 |
| 7 | 2.50 | 3.50 | 2.75 | 3.25 | 2.25 | 2.25 | 3.00 | 3.00 | 2.25 | 2.75 | 2.75 | 2.75 |
| 8 | 2.75 | 3.25 | 2.75 | 3.00 | 2.75 | 2.75 | 3.00 | 3.00 | 2.75 | 2.75 | 3.00 | 3.00 |
| 9 | 2.25 | 3.25 | 2.75 | 2.75 | 3.00 | 3.00 | 3.25 | 3.25 | 3.50 | 3.50 | 3.00 | 3.25 |
| 10 | 3.00 | 3.50 | 2.75 | 3.00 | 2.75 | 2.75 | 3.00 | 3.00 | 2.50 | 3.50 | 3.50 | 3.50 |
| 11 | 3.00 | 3.50 | 2.50 | 3.25 | 2.00 | 2.00 | 4.00 | 4.00 | 3.00 | 3.00 | 3.50 | 3.75 |
| 12 | 2.25 | 3.00 | 2.25 | 2.50 | 2.00 | 2.00 | 3.00 | 3.00 | 1.75 | 2.75 | 2.25 | 3.00 |
| 13 | 2.75 | 3.25 | 2.50 | 3.25 | 2.50 | 2.50 | 3.75 | 3.75 | 2.00 | 2.75 | 3.50 | 3.50 |
| 14 | 3.25 | 3.50 | 3.00 | 3.25 | 3.75 | 3.75 | 3.50 | 3.75 | 3.00 | 3.25 | 3.50 | 3.50 |
| 15 | 3.00 | 3.50 | 2.50 | 2.75 | 3.25 | 3.25 | 3.25 | 3.25 | 2.50 | 3.50 | 3.25 | 3.25 |
| 16 | 2.00 | 2.50 | 2.00 | 2.50 | 2.00 | 2.00 | 4.00 | 4.00 | 3.25 | 3.50 | 4.00 | 4.00 |
| 17 | 2.00 | 2.50 | 2.00 | 2.25 | 3.00 | 3.00 | 3.25 | 3.25 | 2.25 | 3.25 | 3.00 | 3.25 |
| 18 | 2.75 | 3.25 | 2.75 | 3.00 | 2.50 | 2.50 | 3.25 | 3.25 | 3.00 | 3.00 | 3.00 | 3.25 |
| 19 | 2.50 | 3.25 | 3.00 | 3.25 | 2.75 | 2.75 | 3.50 | 3.50 | 3.00 | 3.50 | 3.25 | 3.25 |
| 20 | 2.75 | 3.25 | 3.00 | 3.25 | 2.75 | 2.75 | 3.25 | 3.25 | 3.25 | 3.50 | 3.00 | 3.00 |
| 21 | 2.25 | 3.25 | 2.25 | 2.75 | 2.75 | 2.75 | 3.00 | 3.00 | 2.75 | 3.25 | 2.50 | 2.75 |
| 22 | 2.25 | 3.00 | 2.75 | 3.25 | 2.50 | 2.50 | 3.00 | 3.00 | 2.00 | 3.00 | 2.00 | 3.00 |
| 23 | 2.50 | 2.75 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.25 | 3.50 | 3.50 | 3.00 | 3.25 |
| 24 | 2.25 | 3.25 | 2.75 | 3.00 | 2.00 | 2.25 | 3.00 | 3.00 | 3.00 | 3.25 | 3.00 | 3.00 |
| 25 | 3.00 | 3.00 | 2.50 | 3.25 | 2.75 | 2.75 | 3.00 | 3.00 | 2.75 | 3.25 | 3.00 | 3.00 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 3.00 | 3.00 | 2.75 | 3.00 | 2.75 | 2.75 | 3.25 | 3.25 | 3.00 | 3.75 | 2.50 | 2.75 |
| 27 | 2.75 | 3.25 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 2.50 | 3.75 | 3.25 | 3.25 |
| 28 | 2.25 | 3.00 | 2.50 | 2.75 | 2.00 | 2.00 | 3.00 | 3.25 | 2.00 | 3.50 | 2.75 | 2.75 |
| 29 | 2.00 | 2.50 | 2.75 | 3.00 | 2.50 | 2.50 | 3.25 | 3.25 | 2.75 | 3.25 | 2.00 | 2.75 |
| 30 | 2.25 | 3.00 | 2.75 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.25 | 3.00 | 3.00 |
| 31 | 2.50 | 3.25 | 2.25 | 3.00 | 2.00 | 2.00 | 3.00 | 3.00 | 2.00 | 3.00 | 2.00 | 2.75 |
| 32 | 2.00 | 3.25 | 2.25 | 2.50 | 2.00 | 2.00 | 3.00 | 3.00 | 1.25 | 3.00 | 2.00 | 2.75 |
| 33 | 2.25 | 3.25 | 2.50 | 2.50 | 2.50 | 2.50 | 3.25 | 3.25 | 3.25 | 3.50 | 1.50 | 3.00 |
| 34 | 2.75 | 3.25 | 2.00 | 2.75 | 2.00 | 2.25 | 3.00 | 3.00 | 2.25 | 3.50 | 3.00 | 3.00 |
| 35 | 2.25 | 3.00 | 2.75 | 2.75 | 2.00 | 2.00 | 3.25 | 3.25 | 2.00 | 3.50 | 3.00 | 3.00 |
| 36 | 2.75 | 3.25 | 2.75 | 3.00 | 2.75 | 2.75 | 3.00 | 3.00 | 2.00 | 3.00 | 2.25 | 2.50 |
| AVG | 2.58 | 3.18 | 2.66 | 2.97 | 2.57 | 2.59 | 3.22 | 3.24 | 2.63 | 3.24 | 2.90 | 3.11 |

A paired samples t-test was used to evaluate if there was a significant difference of teamwork skills performance. The results of the t-test before and after VR training exercise is as shown in Table 6-2. VR training exercise is significant impact on coordination ($t = -12.704; p = 0 < 0.05$), decision making ($t = -8.002; p = 0 < 0.05$), adaptability ($t = -7.584$; $p = 0 < 0.05$), and communication ($t = -3.645; p = 0.001 < 0.05$). However, the leadership ($t = -1.784; p = 0.083 > 0.05$) and interpersonal skill ($t = -1.784; p = 0.083 > 0.05$) was not significantly different after VR training exercise. All the comparative t-tests results have been validated through Cohen's benchmark (Cohen, 1988). The value of Cohen's d for 95% confidence interval was tested on a scale of medium to large size effect which is 1.83 for coordination, 0.95 for decision making, and 0.79 for leadership, 0.06 for interpersonal skill, 1.35 for adaptability and 0.46 for communication.

Table 6-2: The paired samples test results

| | Paired Differences | | | | | $t$ | $df$ | $p$ value |
|---|---|---|---|---|---|---|---|---|
| | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference | | | | |
| | | | | Lower | Upper | | | |
| Coordination | -0.597 | 0.282 | 0.047 | -0.693 | -0.502 | -12.70 | 35 | 0 |
| Decision making | -0.313 | 0.234 | 0.039 | -0.392 | -0.233 | -8.002 | 35 | 0 |
| Leadership | -0.021 | 0.070 | 0.012 | -0.045 | 0.003 | -1.784 | 35 | 0.083 |
| Interpersonal | -0.021 | 0.070 | 0.012 | -0.045 | 0.003 | -1.784 | 35 | 0.083 |
| Adaptability | -0.611 | 0.483 | 0.081 | -0.775 | -0.448 | -7.584 | 35 | 0 |
| Communication | -0.215 | 0.354 | 0.059 | -0.335 | -0.095 | -3.645 | 35 | 0.001 |

As can be seen Table 6-1 and Table 6-2, the significant improvement of after VR collaborative training exercise includes coordination, decision making, and adaptability. The average scores of leadership and interpersonal skill have not been improved significantly compared with other teamwork skills categories. This shows that there is no significant difference between before-after VR collaborative training exercises for trainees to improve how to drive the scaffolding construction project to completion and interact cooperatively with team member. The advantages of VR collaborative training exercises is that it helps the trainees enhance the ability of organizing team activities and make decision by useful information to solve the problem. As stated by one of the participants: “Although I did teamwork project before, I could not organise training activities to achieve the training task with my teammate when I operated the scaffolding foundation erection and ground-floor scaffolding erection in virtual environment. However, after a period of VR operation, my teammate and I were able to recognize problems to make team decisions. It really helps me understand more about teamwork through VR practice.”

Another piece of feedback information from participants is that ineffective communication could produce undue stress between trainees, which leads to loss of time and team performance. Good communication is that all team members can voice their opinion. As stated by Wao et al., (2013), good team are built by sharing information and building trust, when each members make the commitment to each other to be a team. As a result, injuries are reduced, and productivity and quality are improved. One participant claimed that “compared with the teamwork I did before, I can practice pro-active listening that is exploring teammate’s ideas rather than debating teammate’s ideas through VR collaborative exercise.”

Even though the average scores of the leadership and interpersonal skills were not significantly different after VR training exercise, the trainees learned through the VR collaborative training exercise that an efficient teamwork needs a good leader to drive the task completion. Based on the observation of the experiment, if a participant was surrounded by people of high competency level, he/she could strive to show his/her potential. Selecting the team members will not automatically make them effectively work as a team. As stated by one of participants: “Although VR training exercise has no impact on my leadership and interpersonal skills, the VR collaborative training makes me deeply understand that if you want to create and manage a team, selecting the team members should not only look for technical skills, but also interpersonal skills.”

## 6.6 Summary

The questionnaire results indicate that VR collaborative training exercise can have positive effect on teamwork skills, especially in coordination, decision making, adaptability and communication. Although the results show there is no significant difference in leadership and interpersonal skills after VR collaborative training exercise, the trainees realise that if relationship between the participants becomes strained, this could result in a task becoming unsuccessful.

This VR collaborative training exercise is a relatively small scaffolding scenario and only two trainees work as a team. In reality, the scaffolding construction task may be completed by more than two scaffolders with the potential of cooperation. In addition, only scaffolding erection process is adopted for evaluation. Potential research can include more complicated operation simulation.

# Chapter 7: Conclusions, implications and future recommendation

This chapter summarises the research findings relating to research objectives. It also provides the theoretical contributions and practical implications of this research. Section 7.1 provides thesis conclusions. Section 7.2 summarises the theoretical contributions. Section 7.3 provides practical implications and Section 7.4 states the research limitations and future study.

## 7.1 Conclusions

### 7.1.1 Research finding for objective 1

**Objective 1: To identify VR-related research and application in construction engineering education and training, as well as lean implementation in the construction sector.**

This objective has been achieved. The findings are:

1. Lean construction research, as well as VR technologies and applications in construction engineering education and training were reviewed.

2. Lean implementation related to productivity and health and safety in the construction industry and education sector were identified, including:

- The adoption of lean practice in the construction industry can have a positive impact on construction health and safety and productivity, and can possibly reduce construction accident rates.
- Lean implementation in the education sector can reduce cost and education cycle time and increase the satisfaction level for students, overall learning process, student academic experiences, and productivity.

3. VSM, as one of commonly used lean tool for construction and education implementations, was investigated:

- VSM is an effective lean tool to identify process wastes and propose actions for improvement across the value flow in the construction industry.
- VSM can also be used to map the educational process in engineering curriculum to better satisfy learning outcomes.
- The implementation of VSM in construction related operation for productivity improvement needs to be investigated.

4. VR-related research and application in construction engineering education and training were reviewed:

- The advantages of adopting VR technologies in construction engineering education and training include enriched intractability, intuitive replicate of the reality, cost-saving, and safety guarantees.
- VR training programmes usually adopt traditional one-size-fits-all training methods that rarely consider the diversity of learning needs among individual trainees. There is a need to investigate how VSM as a lean tool, can be applied to help improve the traditional VR training performance.

### 7.1.2 Research finding for objective 2

**Objective 2: To integrate the lean construction and work postures in TAM projects to simultaneously achieve improved workflow and optimised risk index.**

1. A case study approach was adopted to integrate lean and work posture analysis in a scaffolding installation project:
   - Waste elimination not only affects scaffolding operation process improvement, but also the health and safety of onsite employees who are responsible for scaffolding installation.
   - After a successful VSM implementation, the processing time decreases from 1680 mins to 1172 mins (a 30% reduction), and the percentage of value added time increases from 25% to 37%. In addition, the improved risk value of the scaffolding erection process is reduced to 200 from 265 (a 24.5% reduction).
   - Although there is a general declining trend, i.e. as reduced waste time increases, the risk level declines, such trend is not linear. An optimised solution exists.

2. Based on the case study, an optimisation strategy was developed to ensure that minimum risk index can be achieved by eliminating waste following the VSM procedure:

- The first process in the optimisation is to determine the activities which can have an impact on risk once the waste within the activities is removed.
- The second step in the optimisation is to determine the potential waste time removal interval.

- The finial process is to identify the combination of activities in each waste removal interval and update the risk value of process once waste is removed.

### 7.1.3 Research finding for objective 3

**Objective 3: To develop an innovative VR- and lean-based platform for the education and training in scaffolding erection in TAM projects.**

1. A virtual scaffolding erection scenario was developed for before-after training experiment:

- The virtual models including the scaffolding components, foundations and tanks to be inspected were created using Autodesk Revit 2018. The scaffolding components include 22 base plates, 22 standards, 62 transoms and ledgers, and 10 diagonal bracings.
- The scaffolding components in Autodesk Revit were exported in the FBX format and imported the virtual environment. The virtual scenario was modeled using Unity3D.

2. A new VSM-based VR personalised training protocol was proposed for integrating lean concepts in training guidance. The proposed training method introduced VSM as a lean tool to assist the achievement of three objectives:

- Performance analysis and waste identification on trainees' exercise results.
- Performance profiling based on performance analysis and waste identification for trainers to provide personalised coaching.
- Productivity estimation for identifying trainees' potential improvement.

### 7.1.4 Research finding for objective 4

**Objective 4: To systematically evaluate the effectiveness of the platform for training improvement.**

1. The training performance resulting from the VSM-based VR approach was compared with conventional VR training. Significant improvements were obtained:

- Compared with a baseline training, traditional VR and VSM-based VR approaches can improve WT reduction by 21% and 50% respectively, error count reduction by 12% and 53% respectively, and PT reduction by

12% and 34% respectively. In addition, VAT can be critically improved by the personalized training approach from 7% to 14%.

- The training productivity index of conventional VR training and VSM-based VR training were 3.76 and 4.24, respectively. The productivity was improved by approximately 12%.
- The VSM-based personalised training is advantageous over the conventional VR training in terms of trainees' confidence, including 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).

2. VR collaborative training has positive impact on teamwork skills, including coordination (t=-12.704; p=0<0.05), decision making (t=-8.002; p=0<0.05), adaptability (t=-7.584; p=0<0.05), and communication (t=-3.645; p=0.001<0.05).

## 7.2 Summary of theoretical contributions

This thesis is motivated by integrating lean and work postures to simultaneously improve productivity and health and safety and developing a VR-based platform for effective education and training in TAM projects. The main theoretical contributions of this thesis include:

**1. How does the lean philosophy contribute to construction health and safety?**

Compared with prior studies which argue that the adoption of lean has positive impact on operational health and safety (e.g. Nahmens and Ikuma, 2009; Ikuma et al., 2010； and Gambatese et al., 2016), this study provides an empirical evidence related to the relationship between one lean tool, VSM and occupational health and safety. The distinct implication is related to the question whether the implementation of VSM can help achieve improvement in health and safety of onsite workers. From this case study, it is apparent that the implementation of VSM can help eliminate waste in the installation process, therefore eliminating potential health and safety risks corresponded to the waste. This finding is in accordance with previous studies such as Ikuma et al. (2010). However, it is also found that although the implementation of lean is beneficial, health and safety of onsite workers does not always improve as the implementation of lean intensifies, i.e. more sources of waste are eliminated. This finding suggests that lean attributes and health and safety attributes are two distinct sources of attributes of onsite assembly and installation activities. While some waste activities (e.g. activities that involve the lifting of unnecessary heavy components) contain both attributes and the eliminate of these waste activities can achieve improved performance in both productivity and health and safety, there remain many other waste activities which have very limited health and safety attributes and the eliminate of these activities will have no implications on the health and safety performance of onsite assembly. This finding is in contradiction to previous studies, such as Gambatese et al. (2016), which only identified the alignment relationship between lean and health and safety. Through the optimisation approach and the validation of the approach in a case study, it is found that lean attributes and health and safety attributes are two distinct sources of attributes of onsite assembly and installation. It can be generally concluded that the implementation of lean can have positive health and safety impact. However, higher positive impact may not be observed as lean implementation intensifies. In addition, there is an optimised solution for a combined improvement in lean and health and safety, which can be achieved through a three-step process of determining the waste activities that have health and safety impact, determining the waste removal intervals and determining and updating the removal scenarios.

**2. A new lean- and VR-based training protocol for productivity improvement.**

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 thesis developed a systematic VSM-based VR personalized training protocol to enrich the learning tools of operation training by integrating lean thinking into the training process. A before–after experiment based on a virtual scaffolding erection scenario was established to simulate the training process. It is found that VSM can be applied to help improve operation training performances through an immersive VR-based personalized training program. Compared with conventional VR training processes, VSM-based VR training can effectively improve training productivity, especially in waste identification and error reduction.

## 7.3 Practical implications

This thesis represents an effort to help onsite worker in LNG industry achieve a balanced improvement in both productivity and health and safety, also help onsite worker improve training productivity.

An implication of this study is the development of an optimisation method to identify wastes that should be prioritized to be eliminated. It starts with a three-step process of determining the activities which can have an impact on the OWAS risk category. Based on the specific reduction target, all or part of these waste activities can be removed using the reduction algorithm. The final risk value of the process can then be updated to see whether the solution can help achieve the improvement target. Compared to previous studies which rely on qualitative assessment of lean and health and safety, this study is more readily to be implemented at the site level for simultaneous improvement in lean and health and safety.

Compared with prior studies, this study provides an example of how VSM, as one of the lean tools, can help VR personalised operation training to improve training productivity. A systematic VSM-based VR personalised 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.

## 7.4 Limitations and future research

Even though the VR- and lean- based training platform can effectively improve training productivity, there remain some issues that need to be resolved for future research.

First, the review of the use of VR in CEET covers only the technologies that are related to the CEET field. As such, it does not cover the full spectrum of the development of these technologies. The review also points out a few future research directions. The technology has not yet been fully tested on its suitability and capability with emerging engineering education paradigms, such as flipped classroom. In addition, its suitability with other emerging VR-related educational toolkits and other visualisation approaches should be investigated. The development of BIM and Smart

Cities can be referred to as a source which can provide useful objects to ease the creation process of virtual objects for CEET activities. It is expected that the findings of this research can be a useful reference, contributing to future research or practice on implementing VR for education and training in construction and engineering.

Second, the case study is a relatively small project. Only the removal of waste in six activities has a direct impact on the risk value. As such, the waste removal time interval is permutation of these six activities. For larger projects, there will be more than six such activities and the permutation will be more complicated. However, this does not restrict the use of the optimisation approach. In addition, health and safety in construction industry covers a wide range of issues related to working environment, excessive stress, human error and ergonomics. This study uses work posture as a proxy indicator for health and safety. It is therefore recommended that more performance indicators should be used in future research, which can help improve the discussion related to the complex relationship between lean and health and safety.

Third, all the test participants in VR experiment are 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. In addition, 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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# Appendix

## Appendix 1 List of Publications

1. **Wang, P**., Wu, P., Wang, J., Chi, H.L., & Wang, X., (2018). A critical review of the use of virtual reality in construction engineering education and training. *International Journal of Environmental Research & Public Health*, 15(6), 1204.
2. **Wang, P**., Wu, P., Wang, X., Chen, X., & Zhou, T., (2020). Developing optimal scaffolding erection through the integration of lean and work posture analysis. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-04-2019-0193
3. **Wang, P**., Wu, P., Chi, H.L., & Li, X., (2020). Adopting lean thinking in virtual reality-based personalized operation training using value stream mapping. *Automation in Construction*. http://doi.org/10.1016/j.autcon.2020.103355.

## Appendix 2 Questionnaire of Teamwork Skills for Training Collaboration.

| | | | 1.Very poor | 2.Poor | 3.OK | 4.Good | 5.Very Good |
|---|---|---|---|---|---|---|---|
| 1 | Coordination | When I work as part of a team, I ensure the instructions are understood by all the team members prior to starting the task. | | | | | |
| 2 | | When I work as part of a team, I help ensure the proper balancing of the workload. | | | | | |
| 3 | | When I work as part of a team, I do my part of the organization in a timely manner. | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4 | | When I work as part of a team, I track other team members' progress. | | | | | |
| 5 | Decision making | When I work as part of a team, I know the process of making a decision. | | | | | |
| 6 | | When I work as part of a team, I prepare sufficiently to make a decision | | | | | |
| 7 | | When I work as part of a team, I solicit input for decision making from my team members. | | | | | |
| 8 | | When I work as part of a team, I am able to change decisions based upon new information. | | | | | |
| 9 | Leadership | When I work as part of a team, I exercise leadership. | | | | | |
| 10 | | When I work as part of a team, I lead when appropriate, mobilizing the group for high performance. | | | | | |
| 11 | | When I work as part of a team, I lead the team effectively. | | | | | |
| 12 | | When I work as part of a team, I demonstrate leadership to ensure team results. | | | | | |
| 13 | Interpersonal | When I work as part of a team, I interact cooperatively with other team members. | | | | | |
| 14 | | When I work as part of a team, I respect the thoughts and opinions of others in the team. | | | | | |
| 15 | | When I work as part of a team, I treat others with courtesy. | | | | | |
| 16 | | When I work as part of a team, I treat all my team members as equals. | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 17 | Adaptability | When I work as part of a team, I ask for the instructions to be clarified when it appears not all the team members understand the task. | | | | | |
| 18 | | When I work as part of a team, I can identify potential problems readily. | | | | | |
| 19 | | When I work as part of a team, I willingly contribute solutions to resolve problems. | | | | | |
| 20 | | When I work as part of a team, I seek and respond to feedback. | | | | | |
| 21 | Communication | When I work as part of a team, I communicate in a manner to ensure mutual understanding. | | | | | |
| 22 | | When I work as part of a team, I listen attentively. | | | | | |
| 23 | | When I work as part of a team, I clearly and accurately exchange information. | | | | | |
| 24 | | When I work as part of a team, I pay attention to what others are saying. | | | | | |