Department of Construction Management

Enhanced Value Stream Mapping for Improving Turnaround Process Efficiency in Oil and Gas Industry

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DECLARATION

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

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

Signature:

Date: 16/3/2018

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ABSTRACT

The oil and gas industry has been seeking to improve operational productivity to remain competitive. Turnaround maintenance (TAM), as a periodic comprehensive program, contributes significantly to the long-term stability and continuous production availability of oil and gas plants. However, TAM projects are known for its complexity because of the involvement of massive man powers and resources during planning and operation. It is reported that a major TAM project can potentially cause an annual loss of production availability of 2-3%. Value stream mapping (VSM) is an essential lean technique to eliminate waste by categorising all activities into value adding (VA) and non-value adding (NVA) in the production process. Although VSM has been widely adopted for improving process performance in various sectors, including manufacturing, construction, and healthcare, limited research has been conducted to implement VSM in a TAM project.

The primary aim of this research is to develop an enhanced-Value Stream Mapping (enhanced-VSM) framework to effectively improve TAM efficiency by eliminating waste so as to reduce schedule delay and cost overruns. Firstly, a cross-sector investigation of VSM implementations in manufacturing, healthcare, construction, product development, and service sectors is conducted. Following the review, a clear and standardised VA and NVA classification system is developed for TAM projects using literature review and focus group studies. The classification is then validated using structured interview and finally evaluated using a case study. The results show that the classification system can be effectively used to categorise TAM activities into three groups of activities, including VA, NVA but necessary, and waste.

Based on the classification system, an enhanced-VSM framework is then developed to facilitate a structured application of VSM in TAM projects. The framework includes five major pillars, which are critical work scope selection, current state mapping and measurement, waste analysis, future state improvement, and an Action Plan. A case study on valve replacement in TAM projects is conducted to evaluate the efficiency of the proposed framework. The results show that the enhanced-VSM framework can help reduce the total processing from 49.15 hours to 40.19 hours and increase the ratio of VA activities to 60.37% from 49.33%.

Finally, the Building Information Modelling (BIM) technology is used to manage VSM implementations in a TAM project. The BIM implementations include: (1) 3D BIM model reconstruction from as-built point cloud data; (2) 4D BIM simulation in four different levels (i.e. plant, system, batch, and activity); and (3) constructability review through a cloud BIM-

based collaboration platform. By implementing BIM, the TAM project starts on time and finishes six days ahead of the original schedule.

Theoretical and practical implications of this research are also provided for both VSM researchers and practitioners. This research extends the VSM application beyond the traditional manufacturing production to a TAM process. The theoretical enhancements made to the conventional VSM method include redefining VA and NVA activities in TAM projects, redesigning the traditional VSM into an enhanced-VSM framework in TAM projects and the incorporation of BIM to develop Action Plans to manage VSM implementations. This research also provides three key practical contributions, i.e. a detailed guideline to help users identify VA and NVA activities in TAM projects, a structured approach to implement the enhanced-VSM, and a BIM-enabled approach to eliminate waste in TAM projects. It is expected that by applying the proposed enhanced-VSM framework in TAM projects, long-term improvement on productivity, sustainability and health and safety can be achieved.

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LIST OF ABBREVIATIONS

VSM	Value Stream Mapping
TAM	Turnaround Maintenance
CPM	Critical Path Method
PERT	Program Evaluation Review Technique
VA	Value Adding
NVA	Non-Value Adding
BIM	Building Information Modelling
3D	Three-Dimensional
4D BIM	Four Dimensional Building Information Modelling
WIP	Work In Progress
CONWIP	Constant Work In Progress
JIT	Just-In-Time
SMED	Single-Minute Exchange Of Dies
FIFO	First-In, First-Out
TPM	Total Productive Maintenance
WP	Work Package
WO	Work Order
DES	Discrete Event Simulation
CADD	Computer-Aided Design Drawings
RFID	Radio Frequency Identification
UAV	Unmanned Aerial Vehicle
CSCM	Construction Supply Chain Management
GIS	Geographic Information Sciences
LNG	Liquefied Natural Gas
CSF	Critical Success Factor
LT	Lead Time
CT	Cycle Time
PT	Processing Time
VAT	Value Adding Time
NVATBN	Non-Value Adding Time But Necessary
PTV	Processing Time Variation
STV	Start Time Variation

Chapter 1: Introduction

1.1 Introduction

The Oil and Gas industry is a major contributor to Australia's current economic prosperity. It consists of large-scale capital-intensive facilities which are operated under rigorous operating conditions. To be competitive in a global market, reliable production plants and high production efficiency are essential to reduce cost and improve competitiveness (Lenahan 2011). It is notable that the performance of production is heavily influenced by maintenance productivity in the Oil and Gas industry (Parida and Kumar 2009). Turnaround maintenance (TAM), as a periodic comprehensive programme which contributes significantly to the long-term stability and continuous production availability of the oil and gas plants, is one of the most important maintenance strategies to minimise the risk of production losses (Duffuaa and Ben Daya 2004). TAM project is known for its complexity due to the involvement of massive man powers and financial resources during its planning and operation. It is reported that a major TAM can potentially cause an annual productivity loss of 2-3% (Bevilacqua, Ciarapica, and Giacchetta 2009). The peculiarities of high labour intensity and capital concentration make TAM project a time-sensitive project that any delay or inefficiency can lead to catastrophic failure.

Traditional project management techniques, such as Critical Path Method (CPM)/ Program Evaluation Review Technique (PERT), are commonly applied to manage TAM projects. However, these methods are believed to be inadequate to accommodate the complexity of TAM projects. For example, a TAM project at Athabasca, Canada reported a loss of US$100-125 million due to schedule delay (Pokharel and Jiao 2008). The challenges such as schedule slippage and cost overrun which can be caused by inadequate planning and management were also reported by Joshi (2004). Recent advances in technologies and tools, such as critical chain (Bevilacqua *et al.* 2009), business process re-engineering, reliability-centred maintenance (Bevilacqua *et al.* 2005), and a risk-based inspection and maintenance system (Bertolini *et al.* 2009), have been applied in TAM projects and led to some cumulative improvements. However, delays and inefficiencies in shutdown have been continuously observed in many cases (Levitt 2004, Utne *et al.* 2012). These challenges, including the growth of demand for oil and gas energy in the global market and increased competition and requirement for lower cost, have forced the Oil and Gas industry to develop new business initiatives in order to survive in the competitive market. A well-organised management process for conducing TAM is an essential part to improve maintenance productivity and drive cost down.

Lean thinking is one of the initiatives which focus on improving production efficiency and productivity by concentrating on waste elimination and value creation from customers' perspective (Holweg 2007). Five lean principles of value, value stream, flow, pull, and perfection were summarised by Womack and Jones (2010) as the framework for organisations to understand the strategic approach of lean transformation. One of the most important lean principles - value stream, is 'the set of all the specific actions required to bring a specific product' (Stone 2012), which defines the work process from the view of 'actions'. Monden (1993) divided these actions into three types: value adding (VA), non-value adding (NVA) but unavoidable, and NVA and immediately avoidable. These actions consider both information and physical flows within the overall supply chain. The value stream principle focuses on the transparency of all the steps in the process to eliminate waste, by providing clear VA steps among all the participants. This principle does not rely on the assessment of individual activity, but instead focusing on a holistic view of the whole value stream, which includes the interdependences of all individual activities.

Value stream mapping (VSM), is considered as an essential lean technique to 'see the whole' of process to rethink systematic functioning (Locher 2011, Singh and Sharma 2009, Serrano Lasa, Castro, and Laburu 2009). Quickly following the success of the application of lean thinking and VSM in the manufacturing industry, other industries, such as healthcare, construction, product development, and service, have adopted this remarkable theory and technique (Shou *et al.* 2017). VSM is globally recognised as one of the main tools in order to assess and plan lean implementations (Abdulmalek and Rajgopal 2007).

The advantages of the advanced lean management theory and techniques have attracted the researchers' attention in the TAM domain. Lean thinking has gained much attention in the Oil and Gas industry to improve the efficiency of the TAM process from planning through to completion (Smith and Hawkins 2004). According to Shou *et al.* (2015), a case study, in terms of the application of VSM to measure process efficiency from the lean perspective showed that the lean concept can be applied in TAM projects. In addition, Melton (2005) also argued that through the implementation of lean thinking, which concentrates on VA recognition and waste elimination, the clients and contractors are able to attain the goal of zero waste (Melton 2005). Striving towards this goal will also bring a number of tangible benefits, which may include lead time reduction and increased value of the operation processes, leading to higher satisfaction level of both clients and contractors (Tyagi *et al.* 2015, Abdulmalek and Rajgopal 2007).

1.2 Problem Statement

This thesis addresses the application of VSM technique in the TAM process in the Oil and Gas industry.

1.2.1 Unclear Influencing Factors on Efficient VSM Application in TAM

VSM has been traditionally used in separate case studies in separate industry sectors, as demonstrated by Matt (2014), Jain *et al.* (2008), and Lacerda, Xambre, and Alvelos (2016). The use of the technique has not been sufficiently examined regarding its application in different production settings (Shou *et al.* 2017). As the lean concept is originated from the manufacturing industry, previous studies related to VSM predominately focus on theories and practical procedures in VSM implementation in the manufacturing sector (Dal Forno *et al.* 2014, Singh and Sharma 2009, Serrano, Ochoa, and Castro 2008, Lacerda, Xambre, and Alvelos 2016). Inspired by the VSM research in the manufacturing sector, scholars in other sectors have devoted extensive research effort to implement VSM to achieve productivity improvement. For example, it has been used to explore the wastes, inefficiencies, and non-value added steps in product development process (Tyagi *et al.* 2015, Schulze *et al.* 2013, Mayrl, McManus, and Boutellier 2013). It is also used as an efficient management system to improve the performance of construction supply chains (Arbulu *et al.* 2003), construction sustainability (Rosenbaum, Toledo, and González 2013), and the execution of activities in house construction (Yu *et al.* 2009). VSM has also been used in a wide range of service sectors to improve healthcare efficiency (Doğan and Unutulmaz 2014, Michael, Naik, and McVicker 2013), and sales process (Barber and Tietje 2008).

However, it should be noted that majority of the studies to discuss the use of VSM are within individual sectors. There is a lack of studies which investigate the VSM implementation across different sectors. The applicability of VSM in the industry sectors other than manufacturing has not been fully investigated. Different industry sectors have fundamental differences in their production, construction or service processes. For example, according to Winch (2003), construction and manufacturing industries have fundamental differences in customer focus, culture/people, workplace organisation and standardisation, the definition of waste and continuous improvement. Compared to the manufacturing industry, constructors do not have control of the supply chain and have less opportunity for training due to high turnover (Wang, Sun, *et al.* 2015). In addition, the production sequence is discretionary to a very large extent and it is a resource paced process rather than machine paced (Wang, Zhang, *et al.* 2015). In addition, according to Prajogo (2005), one notable difference between the service industry and the manufacturing industry is the intangibility and heterogeneity of the outputs of services. The measurement of service is dominated by non-physical elements. Another notable difference is that the consumption and delivery process happen simultaneously in the service industry, which causes extreme difficulty to control the quality of the service output before the delivery. Therefore, a comprehensive review of the VSM application in different sectors is necessary to figure out the potential influencing factors for efficient application in TAM.

1.2.2 Inadequate Definition and Classification of the VA and NVA Activities in TAM

There is a very limited number of studies that are related to the use of VSM in TAM due to the significant differences between the TAM execution and the manufacturing production. It should be noted that the production process in the manufacturing industry is linear and repetitive (Holweg 2007, Mi Dahlgaard-Park and Pettersen 2009). The definitions of value in the manufacturing industry are therefore often limited to physical transformation between manufacturing processes. This leads to a heavy focus on product characteristics only, such as functionality to satisfy the final users, which is related to whether an activity contributes to the form, fit or function of the production flow. If so, the activity is considered as VA, and if not, the activity is categorised as waste that has either necessary or unnecessary nature (McManus 2005). However, in maintenance execution, the focus is on improving plant productivity. Meanwhile, due to the features of TAM projects (such as high cost and duration-driven), maintenance management focuses on improving stability regarding the efficiency of workflow planning and control. The definition of VA activities in TAM projects should not be limited to the analysis of the activities which contribute to the productivity of the plant, but should also include activities which can affect the quality of the production process.

For example, some activities which are pre-requisite to fulfill construction or maintenance need (such as temporary structure erection) can add value, contributing to efficient task execution. However, this type of activities does not add value from external stakeholders', e.g. customers' perspective. According to Womack and Jones (2010), NVA are the activities that do not work directly towards the delivery of the final product. As such, these activities should be considered as NVA. Whereas from the customer's perspective in maintenance management, activities that have pre-requisite nature are supportive and critical to the efficiency of the maintenance process. Therefore, this type of activities should not be considered as NVA or pure waste in the maintenance processes. It seems that the traditional classification of VA and NVA in the manufacturing industry may not be directly applicable to TAM projects.

Moreover, due to the significant size of work to be completed in a short period of time, a general VA and NVA definition in turnaround projects faces a series of difficulties, including:

- a wide variety of activities involving tens of contractors during the process, which can lead to a high level of complexity of on-site activities;

- a high level of complexity of the management structure, which involves multi-level interactions among different stakeholders;
- the involvement of massive resources, which can lead to additional workload in terms of activities to manage resource availability;
- the emphasis on safety consideration, which brings additional considerations in operation, further complicating the on-site operation.

These difficulties demonstrate that the traditional way of classifying VA and NVA in the manufacturing industry may not be applicable to TAM projects. The TAM activities should be carefully identified and classified for a proper lean application.

1.2.3 The Absence of Systematic VSM Application Procedures for TAM Projects

Very limited studies have systematically investigated VSM application in turnaround project management. As such, TAM management has not benefited greatly from the advanced lean technique. Current VSM practices are developed for the manufacturing process. Comparing to the production process in the manufacturing industry, TAM is not a repetitive production process but rather a project presenting a unique work scope and context and is conducted following a unique maintenance process (Bevilacqua, Ciarapica, and Giacchetta 2009). TAM is a project environment in which the involvement of planning and control is part of the project-based production system (Bevilacqua, Ciarapica, and Giacchetta 2009). Different from the process-based production in manufacturing, project-based production system features for one-of-a-kind, on-site production, and complexity (Institute 2000, Salem *et al.* 2006). As Shou *et al.* (2015) also pointed out, VSM can be used in TAM projects, but such unique features of TAM makes the process of delivering a maintenance activity quite different to that of the production work in the manufacturing industry.

Furthermore, TAM can be very complex, not only due to the nature of the work, but also because of the pressure to complete all necessary maintenance activities in a relatively short shutdown period. Therefore, the peculiarities, such as short duration, high capital, labour and material intensity, make TAM a large complex, expensive and time-sensitive project. Although VSM has been applied in other project-based production system, such as the housing construction process (Yu *et al.* 2009), the distinctive features of TAM impede the application of the customised VSM in construction projects to the TAM project. With the full consideration of project characteristics and the unique nature of turnaround process, the challenges that impede the application of VSM to the turnaround process must be addressed so as to formalise a systematic VSM application procedure for TAM projects

1.2.4 The Lack of Efficient Approaches to Develop and Implement Action Plans

The Step of Action Plan development and implementation is critical to transform current state VSM to future state VSM. However, most of the existing VSM researchers have overlooked this step. For instance, the new seven iterative steps of VSM approach developed by Braglia et al (2006) did not discuss the Action Plan development and implementation. The same issue can be also found in the research conducted by Seth and Gupta. (2005), Lian and Landeghem (2007), Tyagi *et al.* (2015), Herique *et al.* (2015), and Seth *et al.* (2017).

For VSM researchers who had developed Action Plans in their research (Lasa *et al.* 2009, Garza-Reyes *et al.* 2018), they rarely discussed the effectiveness and efficiency of the proposed Action Plans. A significant number of researchers only compared the current state VSM with future state VSM to conclude the process improvement. This comparison is not meaningful because in reality, most of companies cannot achieve the future state (Lasa et al 2009). The underlying reasons are varied, but it is clear that the Action Plan itself is either ineffective or very hard to be implemented (Lasa et al 2009). Current approaches for Action Plan development and implementation can be classified into two categories: (1) Workshop-based approaches (Chen *et al.* 2010); and (2) Simulation-based approaches (Ali *et al.* 2015, Alvandi *et al.* 2016, Andrade *et al.* 2016, Atieh *et al.* 2016, Aziz *et al.* 2017, Bal *et al.* 2017, Doğan and Unutulmaz 2016, Helleno *et al.* 2015, Schmidtke *et al.* 2014). The former one is easy to be conducted but heavily rely on participants' personal experience, therefore, the quality of the proposed Action Plan cannot be guaranteed. The latter one is widely utilised to investigate the effect of the lean improvement strategies (i.e. pull, standardisation, and flow) before proceeding to real world application. However, the development of such simulations is time-consuming and difficult because it is hard to get right amount of data in right format. In addition, the main focus of both approaches is to develop an ideal Action Plan not provide guidance of how to implement the Action Plan in real world. In summary, current VSM only hints about the areas of improvements. It does not discuss any feasible and efficient approaches to achieve the improvements.

1.3 Research Aim and Objectives

In order to tackle the four problems summarised in Section 1.2, the principal aim of this thesis is to investigate how VSM can be adapted from the manufacturing industry and applied in the turnaround maintenance environment. More specifically, this thesis intends,

To develop and validate an enhanced VSM framework to help plant operators improve their process efficiency during TAM execution.

In order to achieve this aim, the following four objectives need to be achieved.

***Objective 1*:** To obtain an in-depth understanding of the influencing factors by reviewing current VSM applications in multiple sectors.

In order to address the first research problem (Section 2.2.1), this thesis seeks to: (1) review the VSM implementation in multiple sectors, including manufacturing, healthcare, construction, product development and service sectors; 2) investigate the differences of the VSM implementations in the aforementioned five sectors and the reasons leading to the differences; 3) identify key influencing factors to facility and improve VSM implementations in a TAM environment.

***Objective 2*:** To standardise the definition and classification of VA and NVA activities in turnaround projects.

In order to address the second research problem (Section 2.2.2), this thesis seeks to develop a standardised VA and NVA definition and classification system to facilitate lean application in TAM projects. Reviews of the current definition and classification of VA and NVA in the manufacturing and construction industry, as well as relevant studies on the use of lean in maintenance projects will be conducted. The detailed activities conducted in a TAM project will be reviewed as well to assist the development of the definition and classification. A standardised classification system of VA and NVA activities in TAM projects will then be developed. Finally, the classification will be validated through a detailed case study. The developed and verified VA and NVA classification system serves as guidelines for effective and efficient VSM application in TAM projects.

***Objective 3*:** To develop a systematic Enhanced-VSM framework for improving the efficiency of TAM process.

In order to address the third research problem (Section 2.2.3), this thesis will: 1) review the literature on VSM for TAM; 2) outline the challenges when applying VSM in the TAM context; 3) develop a systematic Enhanced-Value Stream Mapping (Enhanced-VSM) framework for a structured application of VSM to turnaround process; and 4) use a case study to validate the Enhanced-VSM framework for improving process efficiency.

***Objective 4*:** To investigate the capabilities of Four Dimensional (4D) Building Information Modelling (BIM) technique in improving Action Plan development and implementation

In order to address the fourth research problem (Section 2.2.4), 4D BIM technique will be investigated as one of the potential approaches to improve the development and implementation of an Action Plan. 4D BIM has been credited with improving construction planning and control procedures. The integration of 3D model with time information has enabled the effective development of an Action Plan in terms of (1) what actions will occur; (2) who will carry our these actions; (3) By when they will take place, and for how long; (4) what resources (i.e., equipment, materials, and work crews) are needed to carry out these actions; and (5) communication (who should know what?). Due to the lack of research on using 4D BIM in TAM projects, this thesis will firstly discuss the alignment between 4D BIM technique and TAM planning processes. Then, a real TAM project will be presented to demonstrate the effectiveness and efficiency of the proposed 4D BIM technique in transforming current state VSM to future state VSM. Finally, other benefits such as time and cost reduction, and safety improvement will be also calculated and explained.

1.4 Significance and Contribution of the Research

TAM plays an important role in sustaining long-term stability and continuous production of plant. According to Obiajunwa (2012)'s research, it is necessary to shut down every 2 years to avoid unscheduled breakdowns which can have a significant impact on the profitability. A proper TAM can lead to increased reliability and technical integrity that leads to a more predictable workload in the industry and effective maintenance work planning.

Maintenance processes for the turnaround are complex and affected by various uncertain factors, such as weather changes, equipment breakdowns, shortages of skilled labour, and delayed delivery of materials that may result in cost overrun and schedule extension of TAM projects. Planners often fail to consider the combined effect of such factors on the complex construction environment. A study conducted in a TAM event at Athabasca, Canada reported a loss of US$100-125 million due to schedule delay (Pokharel and Jiao 2008). It could be worse if any failure caused by the inefficiency of maintenance planning and control. As stated previously, current management theories and methods can't tackle all the challenges and issues, while the applications of advanced management theories of VSM and other lean production concepts in the oil and gas industry is limited. Applying VSM and relative lean production concepts to deal with the challenges and issues within a specific environmental is the major significance of this study.

Firstly, the review on the VSM implementation in different sectors (*Objective 1*) is considered as significant for the development of VSM knowledge. Current studies to discuss the use of VSM are within individual sectors. Few studies have investigated the potential influencing factors for the efficient VSM application in a diverse environment. The review by comparing VSM implementation in five different sectors can provide a detailed examination of issues and problems related to the use of VSM in TAM environment.

Secondly, the developed standardised classification system to classify VA and NVA activities for lean application in TAM project (*Objective 2*) is another significant contribution of this study. Currently, the definition and classification of value and waste focus on product characteristics of the physical transformation between manufacturing processes. The features of project management which concentrate on managing workflow efficiency is not considered in the traditional manufacturing-driving classification. This one of the main reasons that hinder the application of lean. The standardised classification system developed in this study defines VA and NVA in the project management setting and can provide a structured way to classify activities that align with lean production theory in TAM projects as well.

Thirdly, the proposed Enhanced-VSM framework for facilitating VSM implementation in TAM projects (*Objective 3*) is considered as a significant contribution. Current VSM implementation to quantify and remove waste in TAM projects is still adopting traditional rules and tools. However, the unique features of project-based production as well as the peculiarities of complexity and time-sensitivity of TAM project impede the application of traditional VSM in the turnaround process. It is necessary to develop a systematic VSM implementation framework for thorough considering challenges of VSM application in TAM projects.

Finally, the 4D BIM-enabled approach developed in this study for improving Action Plan development and implementation (*Objective 4*) is useful to accelerate the transformation from current state VSM to future state VSM. Current methods, such as workshop-based or simulation-based approaches, for developing Action Plans are still inefficient, and even worse, both of them have overlooked the Action Plan implementation. With the help of 4D BIM technique, it is possible to develop a feasible and effective Action Plan to achieve future state VSM step by step by taking into account project/organisation resource constraints. Furthermore, during Action Plan implementation stage, 4D BIM technique can also work as a support tool to assure the developed Action Plan is executed accurately.

1.5 Structure of the Thesis

This thesis has eight chapters. As shown in Figure 1-1, each chapter is described as follows:

Chapter 1 is an introductory chapter which provides the background of this study, states the problems, then presents the aim and objectives. This chapter gives highlights of the significance and contribution.

Chapter 2 presents the literature review in the field of lean production, VSM, TAM, and advanced technologies. It contains five sections, the first section reviews the development of lean production and relevant management theories and tools, and the rest four sections correspond to the four objectives in Section 1.2, including VSM application, VA and NVA definition and classification in the manufacturing industry, construction industry and maintenance projects, TAM features and the application of information technologies.

Chapter 3 describes the research methodology deployed in this study. In includes four sections which correspond to the four objectives: (1) research method for reviewing VSM implementation in five different sectors; (2) research method for developing a standardised VA and NVA system; (3) research method for proposed an Enhanced-VSM framework; (4) research method for developing 4D BIM based Action Plan.

Chapter 4 reviews the-state-of-the-art development of VSM in five sectors, which consists of three sections: the analysis of VSM implementation in the five sectors respectively, cross-sector comparison of VSM implementation from four aspects, and summary of the impact factors of VSM implementation in a diverse environment.

Chapter 5 develops a standardised system to classify VA and NVA activities for lean applications in TAM projects, which consists of two main sections: VA and NVA definition and classification. Experts interviews and a sample case study are conducted to evaluate and validate the proposed system.

Chapter 6 develops an innovative Enhanced-VSM framework for a structured application into turnaround process. A case study is conducted to demonstrate and evaluate the framework.

Chapter 7 investigates the capability of 4D BIM technique in improving Action Plan development and implementation. A real TAM project has been selected to demonstrate the effectiveness and efficiency of the proposed 4D BIM technique in transforming current state VSM to future state VSM.

Chapter 8 explains the internal and external validation for this research, its contributions and practical implications. Recommendations for future research are also provided in this chapter.

1.6 Summary

This chapter has presented a general introduction to the overall thesis. The introduction has described the background for the need for this study, set out the central research questions, and proposed main research aim and the objectives to answer the research questions.

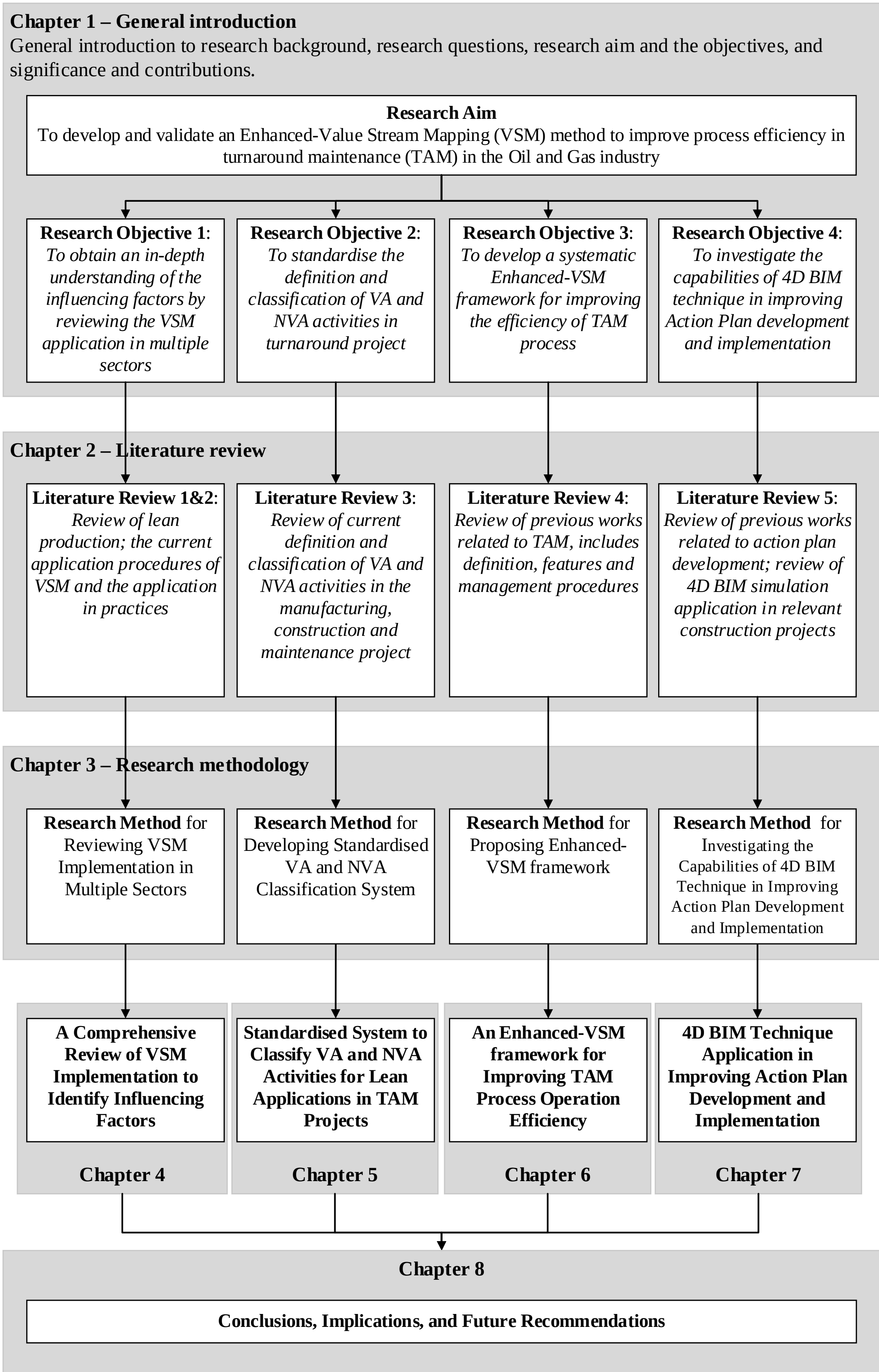

Figure 1-1: Structure of the Thesis

Chapter 2: Literature Review

In this chapter, the definitions of lean production and relevant management theories and tools are reviewed. In addition, the definition and application procedures of VSM are discussed. Specifically, the definition of VA and NVA in manufacturing, construction, and maintenance projects are critically reviewed. The categories of activities in a TAM project are reviewed as well. Finally, the definition and characteristics of TAM, as well as the current practices of VSM application in TAM projects are introduced.

2.1. Lean Production

In this section, the definitions of lean production are introduced, followed by the five lean principles that are commonly adopted. Furthermore, a number of existing lean tools/techniques are discussed. Finally, the definitions and current practices of using lean in maintenance are reviewed.

2.1.1. Lean Production Definition

Lean production is a systematic approach for identifying and eliminating waste through the pull strategy in pursuit of perfection from customers' perspective (Hines, Holweg, and Rich 2004). It originated from the automobile industry, and developed from Taiichi Ohno's notion of 'reduce cost by eliminating waste' (Holweg 2007), which was initially well known as the Toyota Production System (TPS). According to Ohno (1988), TPS relies heavily on the identification and elimination of the seven commonly accepted wastes from Ohno (1988) and Shingo and Dillon (1989). The seven categories of waste consist of overproduction, defects, unnecessary inventory, inappropriate process, excessive transportation, waiting, and unnecessary motion. Womack and Jones (2010) added the eighth type of waste - underutilised employee (as shown in Table 2-1). The identification and elimination of waste is a systematic recognition and expulsion of the factors contributing to the poor quality and fundamental management problems (Monden 2011).

Table 2-1: The Definition of the Eight Categories of Waste in Lean

The type of waste	Definition
Overproduction	The number of goods or information produced is larger and earlier than customers' needs, results in increased inventory.
Defects	Rework and replacement, which waste time and effort.
Unnecessary inventory	Inventory that is not required within a short period, thus increasing the storage cost and risk of obsolescence.

The type of waste	Definition
Inappropriate process	Process costs money and effort without adding value to the customer. Such processes may include rework, reprocessing, overproduction or excess inventory.
Excessive transportation	Materials, work-in-process (WIP), or finished goods move with no value added and result in increased processing time.
Waiting	Workers stand idling and queuing in the process.
Unnecessary motion	Any non-value adding motion that workers have to perform during the process.
Underutilisation of employee	The waste of available knowledge, experience or skill of the staff/workforce by not using these correctly such as placing employees in wrong departments.

TPS is a term that describes the small-lot production management initiatives at Toyota Motor Company. The logic of TPS is to produce a great variety of products in comparatively low volumes to adapt to the economic environment after World War II (Monden 1983, Cusumano 1985). There are two pillars of TPS: Autonomation and Just-In-Time (JIT) (Ohno 1988). Autonomation is the management concept to reduce quality defects. JIT means that only the necessary products are produced at the right time with the right quality (Sugimori *et al.* 1977). It is a comprehensive approach of continuous improvement based on the notion of eliminating all waste in the manufacturing process (Sakakibara, Flynn, and Schroeder 1993). Some of the Toyota management practices, tools or techniques such as Kanban system, five-S, the pull system, total productive maintenance, single-minute exchange of dies (SMED), cellular manufacturing and standardisation were observed and summarised as the underlying components of TPS (Monden 1983).

The term “lean” was first proposed by Krafcik (1988) to describe the manufacturing system used by Toyota. The book *Machine That Changed the World* which published by Womack, Jones, and Roos (1990) used “lean production” to characterise Toyota’s production system. Shah and Ward (2007) (page 791) defined lean production to capture the many facets of lean based on a comprehensive review:

“Lean production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimising supplier, customer, and internal variability.”

Lean production was introduced as a management philosophy that is in contrast to the mass production concept. As shown in Figure 2-1, the detailed evolution of lean production was summarised by Holweg (2007) and Shah and Ward (2007).

1930 and before

1927 - Henry Ford outlines his production philosophy and the basic principles underlying the revolutionary ford production system (FPS) in “today and tomorrow”.

1931 -45

1932 – Ohno joins Toyoda Loom Works as engineering graduate
1935 – Kiichiro Toyoda founds the Toyota Motor Corporation, a spin-off from the Toyoda Loon Works
1936 – production of the Model A starts
1939-45 – Ford uses flow production to produce B-24 bombers at Willow Run. Similar methods are used in the British Spitfire production.
1945 – Toyota restarts car production and builds 3,000 vehicles the same years.

1946 -72

1950 – Labour strikes bring Toyota near bankruptcy. Kiichiro Toyoda resigns, and hands over to Eiji Toyota
1959 – Maxcy and Silberston use labour hours per vehicle as a means to compare international productivity levels
1960 – Fuijo Cho joins Toytota as apprentice, and is mentored by Taiichi Ohno.

1973-88

1973 – oil crisis, North America generates immense interest in the Japanese manufacturing and management practices
1977 – Suginori et al. publish the first academic paper on TPS entitled “Toyota Production System and Kanban System: Materialization and Just-in-Time and Respect-for-Human System”
1978 - Ohno publishes “Toyota Production System” in Japanese
1978 – Jones and Prais analyse assembly productivity differences in their paper “Plant size and productivity in the motor industry: some international comparisons”
1979 – International Motor Vehicle Program (IMVP) starts at MIT
1979 – The repetitive Manufacturing Group is established by APICS. Members include Schonberger and Hall
1981 – Monden publishes a series of articles on TPS in *Industrial Engineering*
1981 – Shingo publishes “a study of the Toyota Production”
1982 – Schonberger publishes “Japanese Manufacturing Techniques”
1982 – Abernathy et al. publish “The competitive status of the U.S. Auto Industry”
1983 - Abernathy et al. publish “Industrial Renaissance”
1983 – Monden publishes “The Toyota Production System”
1983 – Hall publishes “Zero Inventories”
1984 – Altshuleret al. publish “The Future of the Automobile”
1984 – Toyota Motor Company enters NUMMI joint venture with General Motors in California
1986 – The work on the IMVP global assembly plant study begins, benchmarking the performance of 70 plants worldwide
1986 – Krafcik presents IMVP’s first assembly plant benchmark results in “Learning from NUMMI”
1988 – Ohno publishes “Toyota Production System: Beyond large-scale production”
1988 – Krafcik coins the term “lean” to describe the Toyota manufacturing system

1989-2000

1990 – Womack, Jones and Roos publish “The Machine that Changed the World”, showing the results of the first global assembly plant study. “lean production” is used to characterise TPS.
1991 – Clark and Fjimoto publish “Product Development Performance”
1994 - IMVP’s second round of the global assembly plant study is conducted by Macduffile and Pil
1996 – Womack, and Jones publish “Lean Thinking”
1998 – Kochan et al. publish “After Lean Production”
1999 – Fujimoto publishes “The Evolution of a Manufacturing System at Toyota”
2000 – Pil condults the third round of IMVP’s global assembly plant study

2001-07

2001 – Cho announces the “Toyota Way”
2004 – Liker publishes “The Toyota Way”
2004 – Holweg and Pil publish the combined results of all three rounds of the assembly plant study in “The second Century”
2006 – Toyota Motor Company is projected to become the number 1 vehicle manufacturer in the world
2007 – Holweg publishes “The genealogy of lean production”
2007 - Shah and Ward publish “Defining and developing measures of lean production”

2007-now

Numerous books and articles are published to discuss academic conceptual development and empirical practices.

Figure 2-1: The Evolution Procedures of Lean Production (adapted based on Holweg (2007) and Shah and Ward (2007).)

Lean production is a term that is used to describe an effective, high-performance method for managing organisations and delivering their core purpose in the most efficient and effective manner while continuing to develop for a sustainable future (Womack, Jones, and Roos 1990). The basic philosophy of lean production is waste elimination and value creation for the customer (Hines, Holweg, and Rich 2004, Monden 1983, Womack, Jones, and Roos 1990). Over the last decade, lean production has been widely adopted in the manufacturing industry and extended to other industries.

2.1.2. Lean Principles

In order to set up guidelines for the transformation from non-lean to lean, five lean principles, including value, value stream, flow, pull, and perfection are created. The five principles are summarised by Womack and Jones (2010) after about 6 years of investigation following the publication of the book *Machine that Changed the World*. It is considered as the framework for organisation to understand the strategic approach of lean transformation.

Value

Value is described as the quality of products or service that satisfy customer's needs. It can only be defined by the ultimate customer. The focus on customer value causes lean development from an approach of waste and cost reduction to a theory that continuously seeks to enhance customer value, that is, by adding product or service features and removing wasteful activities (Hines, Holweg, and Rich 2004). A precise definition of value through a dialogue with specific customer is considered as the starting point of lean thinking (Womack and Jones 2010).

Value stream

Value stream is 'the set of all specific actions required to bring a specific product' (Stone 2012), which defines the work process from the view of 'actions'. Womack and Jones (2010) divided these actions into three types: VA, NVA but unavoidable, and NVA and immediately avoidable (i.e. pure waste). These actions consider both information and physical flow within the overall supply chain. This principle focuses on the transparency of all the steps and providing clear VA steps among all the participants. Instead of relying on individual value streams, this approach focuses on a holistic view which takes the interdependence of actions into consideration.

Flow

Flow refers to the VA steps in the production process that flow continuously with minimised errors, variations, and interruptions. This principle requires a specific understanding of the relationships of the VA activities (Melton 2005). It means that the material needed for the product is ordered just at the right time, quality and quantities and the product-in-process flows continuously through the production process. The flow principle emphasises on reducing inventory levels and cycle time between the VA activities to achieve a continuous flow (Liker 2004). The lean methods and tools such as continuous flow, production levelling, standardised work, quick changeover, supermarket, First-In, First-Out, and preventive maintenance are developed to establish and maintain the continuous flow.

Pull

Pull means producing only what is needed to supply orders required by the customer at the right time. The operation in pull manufacturing process will only produce the parts in the quantities that are required by the succeeding operation step. In contrast to the mass production system which relies heavily on the forecast of sale, the pull system focuses on matching production with the demand to maintain a low inventory and tight control of production process is needed. The lean tools such as takt time and Kanban were created to enable a pull system.

Perfection

Perfection is systematic a lean thinking for a continuous improvement endeavor. In lean production, continuous improvement facilitates the endless effort to improve process performance by gradually building a lean culture.

2.1.3. The Common Lean Tools

Hines, Holweg, and Rich (2004) argued that there are two levels of lean: operational (shop-floor lean tools) and strategic (customer-centred strategic lean thinking). Lean tools are the lean elements summarised from the fundamental lean philosophy and play as operational instruments to assist lean implementation in practice. The lean tools were summarised from previous studies, such as Womack and Jones (2010), Rother and Shook (2003), Pavnaskar, Gershenson, and Jambekar (2003) and Hines, Holweg, and Rich (2004).

5S

5S consists of sorting (seiri), set in order (seiton), shine (seiso), standardising (seiketsu), and sustaining (shitsuke). It is a waste reducing process to optimise productivity and quality through engage improvement with workstation (Gapp, Fisher, and Kobayashi 2008). It is a management system aims to embed the standardisation and discipline value into the existing configuration.

Visual management

Visual management is a technique that provides visual guide to the production process. It includes all communication devices and methods used in the working environment to guide decision making.

Value stream mapping

Value stream mapping is a technique developed to understand VA and NVA activities in flow through systematic lean strategy. It is considered as the initial tool to assist lean application. Rother and Shook (2003) introduced a systematic VSM application procedure to assist in the practical implementation.

Takt time

Takt time is the unit production rate that is needed to meet customer requirements based on the rate of sale (Rother and Shook 2003). It is the ideal production rhythm for each process and is commonly used to establish a production balance. It is calculated by the following equation:

Take time = the available working time per day/ customer demand rate per day

Continuous flow

Continuous flow is a method for producing one item at a time, with each item being passed on to the next workstation without delay. It is an important management theory to reduce inventory and inefficient operations between value-adding actions.

Pacemaker

Pacemaker is the most downstream activity in the value stream to decide the pace of production of all the upstream activities. It is typically the process at the most downstream of a series of production which has to be revolved to a continuous flow.

Production levelling (Heijunka box)

Production levelling is also known as Heijunka Box. It is the lean tool focusing on distributing the production of different products evenly over a time period to reduce the WIP inventory and the size of buffers. It is a useful tool to increase output variability by balancing the production.

Standardised work

Standardisation is one of the rational theories of lean thinking in TPS. It is a management theory requires details and explicit descriptions of the routine and repetitive work. Standardised work is used to handle variables in production. According to the tool, the production processes and sequences should be specified and standardised in order to reduce the waste caused by variations in the production process.

Quick changeover

Quick changeover refers to the group of methods applied to reduce the time required to switch from producing one type of product to another. The lean tool includes setup reduction and SMED. It enables continuous work flow and mixed production with a pull system.

Kanban

Kanban is one of the most fundamental tools in TPS. Kanban is a visual control card or an information system that controls the production quantities in every process. A Kanban is used in a production process which gives the signal of the time and quantity of the products need to be produced. With the purpose of achieving JIT, Kanban prevents overproduction, extra inventory, and defects.

Supermarket

Supermarket refers to a buffer or storage area located at the finishing end where large amounts of inventory exist. A supermarket is usually placed at where continuous flow is not possible and batching is necessary.

First-In, First-Out (FIFO)

First-In, First-Out (FIFO) production is also referred to as 'CONWIP (constant work-in-process)'. It is located between two continuous processes to substitute for a supermarket and maintain a flow between them. The FIFO method can accommodate a certain amount of inventory and prevent overproduction.

Total productive maintenance (TPM)

Total productive maintenance (TPM) is a production-driven improvement method that is designed to optimise equipment reliability and ensure efficient asset management (Ginder, Robinson, and Robinson 1995). It is a maintenance theory encourage the involvement of all workforces from top to bottom to optimise equipment efficiency and reliability (Ahuja and Khamba 2008).

Self-quality check (Poka-yoke)

Self-quality check (poka-yoke) is a method for early defect detection. WIP products are examined before they are sent to downstream processes. It is a quality management method with an effort to prevent errors from occurring.

Continuous improvement (Kaizen)

Continuous improvement is related to constant actions to reduce and eliminate waste in a continuous way. Its aim is to achieve perfection through the continuous effort for improvement.

2.1.4. The Application of Lean Production

Whipple, Voss, and Closs (2009) suggested that the conceptualisation of lean concept should be divided into three levels in order to create clear understanding: lean philosophy, lean principles and lean tools (Figure 2-2). Lean philosophy focuses on customer-central value and waste. The five lean principles describe the critical program of the philosophy transformation. Massive lean tools are developed to facilitate practical lean application. In previous studies, some contributions have been concentrated on elaborating the lean philosophy at a theoretical level (Hines, Holweg, and Rich 2004, Holweg 2007, Shah and Ward 2007). On the other hand, some studies have focused on the application of lean tools and their relevant performance evaluation. Lean has both strategic and operational dimensions (Hines, Holweg, and Rich 2004).

Hines, Holweg, and Rich (2004) distinct lean thinking to two levels: strategic and operational. Strategic level is the discussion in lean programmes, with a focus on understanding customer-centreed value proposition. Operational level discusses how to apply a series of lean tools and techniques to eliminate waste with the strategic guide. It is argued that both levels should be considered to understand lean as a whole in order to apply the right tools and strategies to provide customer value.

Shah and Ward (2007) defined lean from both philosophical and practical orientations. Philosophical view point is related to guiding principles and overarching goals. Practical is a perspective of a set of management tools, or techniques that can be observed directly. It is argued that the different orientation undermine conceptual clarity.

Based on these two viewpoints, lean production has to be understood as a concept has multiplicity. As shown in Table 2-2, a four possible pathways of lean production was presented (Mi Dahlgaard-Park and Pettersen 2009).

Table 2-2: An Illustration of the Four Pathways of Lean Production (adapted from (Mi Dahlgaard-Park and Pettersen 2009))

	Operational	Strategic
Philosophical	Leanness	Lean thinking
Practical	Toolbox lean	Becoming lean

Shah and Ward (2007) argued that lean production is equivalent to neither the simple application of the guiding principles, such as waste elimination or continuous improvement, nor the underlying elements such as pull, Kanban or employee involvement. Lean production is a multifaceted concept characterised with different sub-dimensions. On the journey of "becoming lean", VSM has become a versatile tool for lean production application (Singh and Sharma 2009, Locher 2011). It was considered as the foundation to identify opportunities for various lean techniques and tools (Abdulmalek and Rajgopal 2007, Lian and Van Landeghem 2007). The emphasis on value creation and the understanding of customer-centreed value in both lean strategic development and VSM-based lean operation have made the identification and analysis of VA and NVA an essential activity in the process of lean implementation. Figure 2-2 shows the conceptual development of lean production.

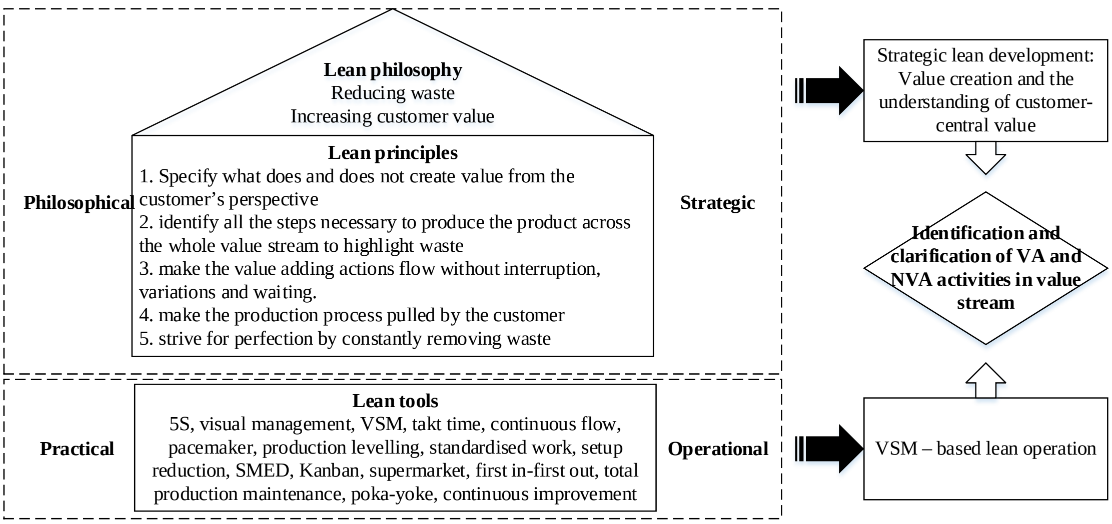

Figure 2-2: The Conceptual Development of Lean Production

2.1.5. Lean Maintenance

Lean thinking has been brought into the maintenance management area to form a strategy that is usually referred to as lean maintenance. The concept was developed based on the TPM, which aims to eliminate production loss and optimise the reliability and effectiveness of manufacturing equipment (Smith and Hawkins 2004).

According to Smith and Hawkins (2004) (page 257), lean maintenance is defined as

"*a proactive maintenance operation employing planned and scheduled maintenance activities through TPM practices, using maintenance strategies developed through application of reliability centred maintenance decision logic and practiced by empowered (self-directed) action teams using the 5S process, weekly Kaizen improvement events, and autonomous maintenance together with multi-skilled, maintenance technician-performed maintenance through the committed use of their work order system and their computer managed maintenance system or enterprise asset management system. They are supported by a distributed, lean maintenance storeroom that provides parts and materials on a JIT basis and backed up by maintenance and reliability engineering group that performs root cause failure analysis, failed part analysis, maintenance procedure effectiveness analysis, predictive maintenance analysis, and trending and analysis of condition monitoring results*".

The definition can be explained by using a maintenance management pyramid as shown in Figure 2-3. Lean maintenance is considered as an integrated frame that includes almost all the maintenance theories and concepts. However, it has been criticised that there are too many concepts included in this definition and some of them are overlapped with each other.

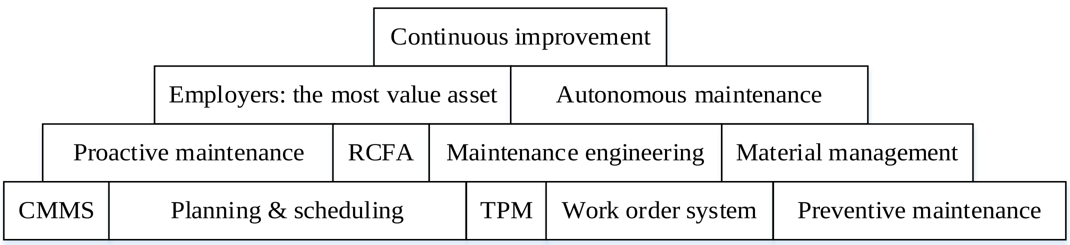

Figure 2-3: Maintenance Management Pyramid (adapted from Smith and Hawkins (2004))

Levitt (2008) defined lean maintenance as delivery of maintenance services to customers with as little waste as possible, or producing a desirable maintenance outcome with the least amount of inputs. The inputs include labour, material, tools and equipment, and management effort. Lean maintenance is to gain improvement in plant reliability, availability and process repeatability (i.e. reduced variation).

Lean maintenance shifts the attention of maintenance improvement from the technical matters to the management side, which focuses on eliminating the root causes of problems through team-based decisions and implementation. According to McCarthy and Rich (2015) and Smith and Hawkins (2004), lean maintenance seeks to eliminate all forms of wastes such as extra inventory in the maintenance process. Reducing wastes in maintenance operation is the main feature that distinguishes the lean maintenance practice from a conventional maintenance management practice.

Mostafa, Dumrak, and Soltan (2015) identified and analysed 43 retrievable lean maintenance publications spread from 2001 to 2014. The lean tools such as VSM, 5S, visual management, TPM, standardised work, inventory management, SEMED, and Poka-Yoke are the key techniques that can be applied to achieve lean maintenance improvement effectively (Smith and Hawkins 2004, Davies and Greenough 2010, Okhovat *et al.* 2012). It also argued that most of the lean maintenance research on the practical application is restricted to the manufacturing industry. Few studies have proposed a comprehensive framework to integrate lean thinking in an operational maintenance environment that sits outside of the manufacturing context.

2.2. Value Stream Mapping

In this section, the definitions of VSM are reviewed. The application procedures of VSM are then introduced. Finally, the applications of VSM are critically reviewed.

2.2.1. The VSM Definition

The concept of VSM was first brought into the lean philosophy in 1995, where VSM was described as a group of suitable techniques for identifying wastes in an individual value stream and applied as an appropriate contingent route towards the removal of wastes (Hines and Rich 1997). Following its origin, seven VSM techniques were summarised by Hines and Rich (1997), namely, process activity mapping, supply-chain response matrix, production variety funnel, quality filter mapping, demand amplification mapping, decision point analysis, and physical structure mapping. However, these techniques are limited at revealing and visualising the link between the nature of the information and the physical flows in the value stream perspective (Pavnaskar, Gershenson, and Jambekar 2003). A different version of VSM has been proposed by Rother and Shook (2003) to address this problem, which is to differentiate the VA and NVA activities in both information and physical flows through a systematic lean strategy for waste elimination and continuous improvement from users' perspective.

2.2.2. The Application Procedures of VSM

VSM is based upon two basic concepts: the visualisation of the VA and NVA activities in both information and physical flows; and the reduction and elimination of NVA or waste to improve process efficiency (Womack and Jones 2010). It provides a process-based view that focuses on the analysis of value stream (Rother and Shook 1999). VSM is normally applied by following a four-step procedure (Rother and Shook 2003, Shou *et al.* 2017).

Step 1: Product family selection

In manufacturing, the repetitive production process is considered as a product family, and the process with the highest value is generally selected as the target for improvement (Tapping and Shuker 2003). Mapping a more complicated system will require investigating a target work which can provide valuable insight into the process efficiency.

Step 2: Current state mapping and analysis

A list of process data should be collected to depict the VA and NVA activities of the current production process. VSM is featured for revealing and visualising the link between the nature of the information and physical flows in the value chain perspective (Pavnaskar, Gershenson, and Jambekar 2003). The analysis of information and physical flows proposed by Rother and Shook (1999) is usually carried out at a shop floor level. Physical flow is a recording of product transfer between the activities of the manufacturing process, and the information flow is a demonstration of the connections between frontline workers and production manager, and between customers, suppliers and project managers. A set of standard icons was designed by Rother and Shook (2003) to unify the drawing of the current state map (Figure 2-4).

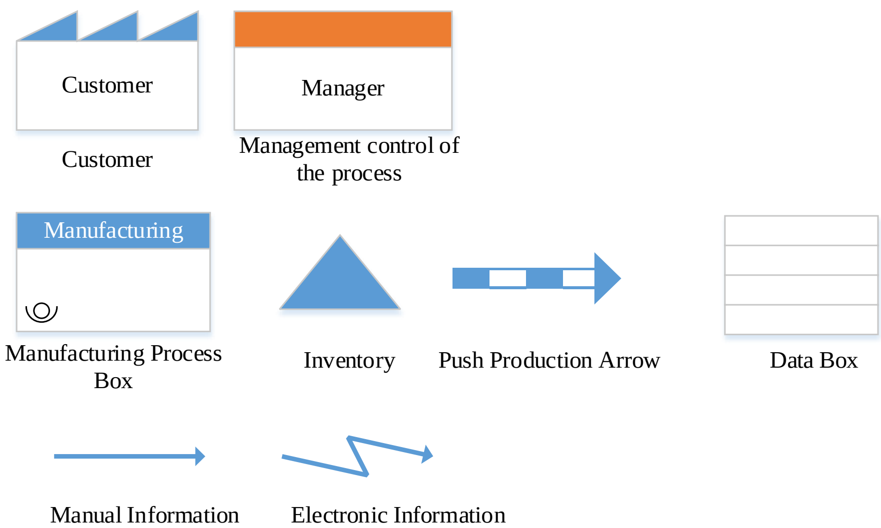

Figure 2-4: The Standard Icons of Current State Map (Rother and Shook 1999)

In the manufacturing environment, waste and value are defined by whether an action contributes to the form, fit or function of the material flow – if so, the action is considered as VA, and if not, it is categorised as waste (Brown, Collins, and McCombs 2006). Many metrics have been created to measure the value and waste in the process (Table 2-3).

Table 2-3: Metrics Used for Current State Analysis (Rother and Shook 1999)

Metrics	Descriptions
Cycle time	The time required for completing a product in a process
Lead-time	The total time required for the completion of a production process
Value added time	The time that the customer is willing to pay for
Changeover time	The time that switches the production from one product type to another
Uptime	The proportion of available time that is actually used to produce a product of an on-demand machine
Inventory	The materials and products that are stored in the value stream
WIP inventory	The uncompleted products that are stored in the value stream
Manpower	The human resources that are required to operate the production process
Production batch sizes	The products that will be produced from the production
Product variations	The changes that happen for a product in the value stream
Defects	The poor-quality products produced in the value stream

Step 3: Future state improvement

A systematic procedure of future state improvement guidelines has been summarised based on Rother and Shook (2003)'s VSM theory. A series of lean tools can be applied, following the 8 questions that are used to streamline the waste elimination procedure, as shown in Table 2-4 (Abdulmalek and Rajgopal 2007, Braglia, Carmignani, and Zammori 2006). Figure 2-5 illustrates the icons used for drawing the future state map.

Table 2-4: Guidelines for Future State Improvement (Abdulmalek and Rajgopal 2007, Braglia, Carmignani, and Zammori 2006)

	Future state questions
Basic	What is the takt time? Will finished goods be built or replenished to supermarket, or will they be built and directly shipped to clients? Where can continuous flow processing be utilised? Is there a need for a supermarket pull system within the value stream (Kanban-CONWIP)? What single point in the production chain will be used to schedule production?
Heijunka	How will the production be leveled at the pacemaker process? What increment of work will be consistently released from the pacemaker process (pitch)?
Kaizen	What process improvements will be needed?

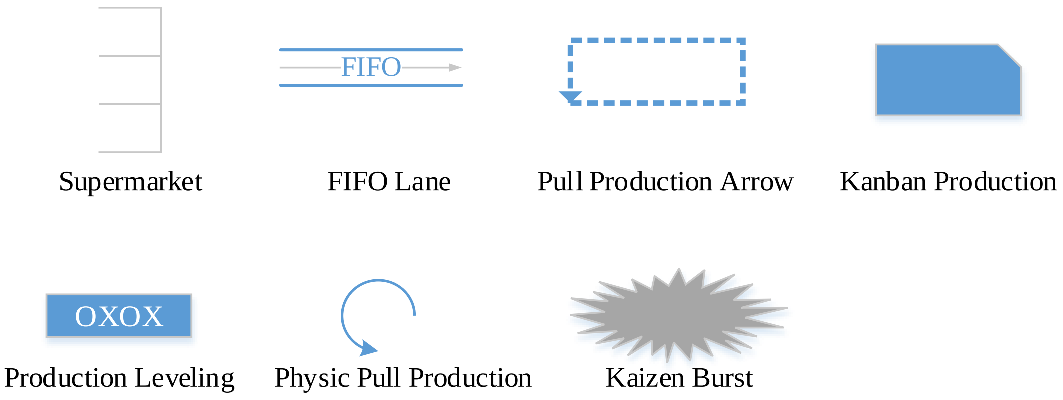

Figure 2-5: The Standard Icons of Future State Map (Rother and Shook 1999)

Step 4: Action Plan for the Application of Future State Improvement

An Action Plan and some management guidelines are developed for achieving the future state. In manufacturing, the output is uniform. It is straightforward to develop and implement a lean system to continually improve the repetitive process.

2.2.3. The Application of VSM

There are many studies related to VSM application. The benefits of VSM are reported by Seth and Gupta (2005) for promoting lean application and reducing cycle time. Abdulmalek and Rajgopal (2007) investigated the benefits of VSM in reducing lead-time and WIP inventory.

Similar benefits, such as reduced waste in the supply chain (Jain *et al.*, 2008), continuous improvement (Chen *et al.*, 2010), reduced lead time (Tyagi *et al.*, 2015) and enhanced organisational performance (Sunk *et al*., 2016), have also been reported. However, during the implementations, some limitations of VSM have been identified (Braglia, Carmignani, and Zammori 2006, Serrano, Ochoa, and Castro 2008, Braglia, Frosolini, and Zammori 2009).

- VSM is only applicable for high volume and low variety production
- VSM is a paper-and-pencil-based technique that can only provide static production data
- VSM is designed for manufacturing production process, can only be applied effectively to linear product system
- VSM lacks the spatial structure of the facility layout and how that impacts interoperation material handling delays
- VSM fails to show the impact of inefficient material flows on work in process (WIP), order throughput and operating expenses;

Braglia, Carmignani, and Zammori (2006) proposed a new VSM approach based on seven iterative steps analysis for complex non-linear production systems. Braglia, Frosolini, and Zammori (2009) proposed two alternative approaches based on statistics and fuzzy algebra respectively to include variability analysis in VSM. Henrique *et al.* (2016) applied VSM in the healthcare involvement focused on analysing the three flows: patient flow, information and material flow.

Furthermore, there are several studies which used simulations to enhance VSM by using and analysing data in a dynamic environment. Ever since McDonald, Van Aken, and Rentes (2002) started to use simulation for a dynamic view of VSM, simulation methods are widely used for improving VSM efficiency. Gurumurthy and Kodali (2011) introduced simulation and VSM to design a new lean manufacturing system.

2.3. The Definition and Classification of VA and NVA

In this section, current definition and classification of VA and NVA activities in the manufacturing industry are reviewed. The definition and classification of the VA and NVA concepts in the construction industry are then critically reviewed. Construction project is a typical example of a project-based production and management system. The review of relevant studies in the construction industry can offer useful insights about the classification of VA and VA in the project management area. The applicability of VA and NVA definition and classification in lean maintenance project is discussed. Finally, the identification and classification of maintenance activities in TAM project are reviewed.

2.3.1. The Definition and Classification of VA and NVA in the Manufacturing Industry

Value is considered as the first principle of lean thinking. In order to realise value in the manufacturing process, Ohno (1988) divided the workers' activities into waste and work. According to Ohno (1988), improving the share of VA in workers' activities was the greatest concern whilst developing the TPS. Similarly, Shingo and Dillon (1989) categorised the workers' operations in the production processes to two categories: those that add value and those do not. Thürer, Tomašević, and Stevenson (2016) summarised that both studies and concluded that, by referring to system input and output, waste is any loss in value during the inefficient transformation process. These studies focus on efficiency improvement in the production process by quantifying the ratio between valuable output and consumed valuable resources (Thürer, Tomašević, and Stevenson 2016).

Womack and Jones (2010), on the other hand, focused on the development of a new definition of value - customer-centreed value. Along with the evolution, value is defined from the customers' perspective. The view of value has changed from waste and cost reduction to enhance customers' value by adding product or service features and/or removing wasteful activities (Hines, Holweg, and Rich 2004). Womack and Jones (2010)'s research focused on developing a guideline of waste elimination and value improvement by classifying and quantifying the activities from customers' perspective (Kosonen and Buhanist 1995). Accordingly, the activities in value stream were classified to three types actions: VA, NVA (pure waste), and NVA that is necessary for streamlining the production process to increase the value of the final product (Womack and Jones 2010). This categorisation has also been adopted in many following studies, such as Hines, Holweg, and Rich (2004), Browning (2003), and Sahoo *et al.* (2008).

Moreover, value stream mapping, an essential lean technique proposed by Rother and Shook (2003) to understand VA and NVA activities in flow through systematic lean strategy, has been considered as the fairly generalisable lean implementation framework (Marodin and Saurin 2013). Combined with Womack and Jones (2010)'s work on value and waste classification, the activities in production process were defined and organised systematically from the customers' perspective. Therefore, a clear definition and understanding of VA and NVA in a process become fundamental to embrace modern manufacturing paradigms of lean thinking successfully. Table 2-5 shows the development of the definition of VA and NVA in the manufacturing industry.

Table 2-5: The Development of the Definition of VA and NVA in Manufacturing Industry

Reference	The definition of value	The definition of waste	VA	NVA
The movement of workers are divided into waste and work (Ohno 1988, 57)	Value defined by system input and system output, where any loss in value during the transformation process (inefficiency) is considered to be waste.	"The needless, repetitious movement that must be eliminated immediately. For example, waiting for or stacking subassemblies."	"Value-added work means some kind of processing – changing the shape or character of a product or assembly."	"Non-value-added work may be regarded as waste in the conventional sense"
"The movements of operators can be classified as operation and waste". "There are two types of operations: those that added value and those that do not" (Shingo 1989, 76)		"Waste is any activity that does not contribute to operations, such as waiting, accumulating semi-processed parts, reloading, passing materials from one hand to the other"	"Value-adding operations that actually transform materials, changing either their form or quality."	"Operations that do not add value, such as walking to get parts, unpacking supplied parts, and operating switches, may be considered waste"
"Value stream analysis will almost always show that three types of "Womack and Jones (2010)	Value defined by product/service characteristics by the ultimate customer	"specifically any human activity which absorbs resources but creates no value"		

2.3.2. The Definition and Classification of VA and NVA in the Construction Industry

The construction process has a long schedule span, massive tasks, and multiple participants (Salem *et al.* 2006). The supply of resources (labour, material, and equipment) and the sequence of tasks in the long construction process create numerous variations and flexibilities (Salem *et al.* 2006). Quality management of the construction process as a wider concern other than simple defect prevention, monitoring, and intervention (Salem *et al.* 2006).

Koskela (1992) investigated the introduction of lean in project management, as well as its influence and interaction with project management functions (Koskela 1997, Ballard and Howell 1998). Value maximisation and waste elimination in the project management process are examined from users' perspectives. Through an extensive review of VA and NVA in lean project management literature, it appears that the basic definition used to differentiate VA and NVA activities in project management processes is generally in line with the definition proposed in the manufacturing industry (Viana, Formoso, and Kalsaas 2012, Alarcon 1997, Koskela 2004, Lee *et al.* 1999).

VA and NVA activities in project management are defined according to the Transformation-Flow-Value (TFV) theory proposed by Koskela (1992). TFV theory of production is built on the understanding of production systems and associated production theory and related tools (Koskela 1992). The three basic concepts of Transformation, Flow, and Value transfer the management attention from the schedule, cost and output measures to the value created by all the work processes (Koskela *et al.* 2002). Transformation view discovers which tasks are needed by the customer, the transformation of inputs into outputs generates required value (VA) for the construction process (Koskela 1997). The view of flow composes of transformation, inspection, moving and waiting in the process, the basic thrust is to minimise unnecessary production or operation (NVA) to reduce process variability (Koskela 1997). The view of value generation emphases on fulfilling customers' value, it represents where the task deployed is appropriate to capture the requirement or not (Koskela 1997).

In terms of classifying VA and NVA in project environment, Lee *et al.* (1999) divided construction activities into six groups. Frist, any operations that alter the shape or other characteristics of materials or products are grouped and considered as VA. Then, activities of volume inspection, quality inspection, and transportation are the three groups considered as NVA but necessary. Finally, the activities relevant to storage and delay are grouped respectively and considered as NVA/waste in the process. Diekmann *et al.* (2004) followed Womack and Jones (2010)'s definition but further clarified NVA but necessary and NVA/waste. NVA but necessary is the activities required for construction operation, although these activities do not have effects on the finished product. Some typical NVA but necessary activities include material positioning, in-process inspection, and temporary work and support activities (Diekmann *et al.* 2004). This classification has been adopted by many following lean studies in the construction industry (Höök and Stehn 2008, Yang and Al-Sudairi 2007, da C, Milberg, and Walsh 2012, Gao and Low 2014). Kartam, Ballard, and Ibbs (1997) classified NVA activities as those activities that add no value to the process, but add cost, while the activities such as waiting for materials, waiting for instructions, rework, and inspection are considered NVA activities in the construction process.

However, there are some limitations of such definition. Jørgensen and Emmitt (2008) argued that the concept of customer value is inadaptable to the understanding of value and waste in a project environment due to the involvement of different customers and users within different project phases. Mao and Zhang (2008) also had concerned about the adaptability of the definitions and classifications of VA and NVA in the construction process. For example, Mao and Zhang (2008) stated that support activities such as earth transportation are unavoidable and critical to creating value to the contractor and it is not appropriate to classify VA and NVA activities based on the "transformation" and "flow" concepts. It is also notable that the culture in a project context has different structure, logic, and requirement (Yang and Al-Sudairi 2007), while the TFV theory ignores the impact of these factors.

2.3.3. The Definition and Classification of VA and NVA in Maintenance Project

According to the definition proposed by the Maintenance Engineering Society of Australia, maintenance management is recognised as "the engineering decisions and associated actions necessary and sufficient for the optimisation of specified capability". Capability is referred as the ability to perform a specification within a range of performance levels. The characteristics of capability may include function, capacity, rate, quality, responsiveness, and degradation (Ahuja and Khamba 2008). Due to these features, value in maintenance project focuses on improving reliability, safety, productivity and quality of the plant (Márquez 2007). The maintenance service (i.e. production line) is assumed as an asset considering both completing specific maintenance items and managing the maintenance operation (Mostafa *et al.* 2015). Therefore, value is identified from the asset perspective which can be improving its availability and reliability to complete the essential tasks (Mostafa *et al.* 2015). According to this interpretation, value is created though effective planning and efficient control.

The value concept which is defined by Womack and Jones (2010) is widely accepted for measuring maintenance performance. Any operation in the maintenance process that referred as any action or process that a customer would be willing to pay for is defined as value adding. However, the review revealed most of the lean maintenance discussion is limited to manufacturing industry (Mostafa *et al.* 2015). So the value conception is generally applied, while little research has been found with a further discussion on elaborating VA activities in maintenance projects.

Following the core concept of lean production in terms of eliminating the eight types of waste, lean maintenance focuses on identifying and eliminating waste to specify the value as well. In maintenance system, waste usually consists of outdated procedures, overstocked, underused inventory of equipment, material, parts, as well as wasted labour, time, and transportation (u Yile, XueHang, and Lei 2008). The eight types of waste were redefined based on the characteristics of the activities in maintenance projects. According to Baluch, Abdullah, and Mohtar (2012), Clarke, Mulryan, and Liggan (2010), and Davies and Greenough (2010), waste in maintenance projects may include:

- Unproductive work – work that doesn't need to be done.
- Delays in motion – Waiting times, including delays waiting for parts, machinery, people, etc.
- Unnecessary motion – Unnecessary transportation to tool stores or workshops, looking for items, moving mobile work stations around without good reasons.
- Poor management of inventory – Not able to deliver the right parts at the right time.
- Rework – Repeat tasks, or introduce additional tasks, as a result of poor workmanship.
- Underutilisation of people – Not using people to the limits of their abilities.
- Ineffective data management – Collecting data that has no value, or failing to collect vital data.
- Miss usage of machinery – Incorrect operation leading to maintenance work being done when it is not needed.

Some studies have mentioned the lean and VSM application for improving maintenance process by eliminating waste (Shou *et al.* 2015, Melton 2005, Smith and Hawkins 2004). However, the research on discussing the classification of VA and NVA is marginal. No specific research work has been found out.

2.3.4. The Identification and classification of the Maintenance Activities in TAM project

TAM is a complex maintenance project which consists of thousands of activities during the maintenance execution. The activities conducted in TAM project has to be identified and sorted out in order to attach the value and waste attributes precisely. However, few studies have focused on activity identification and classification.

Ghazali and Halib (2011) proposed to classify TAM activities by institutional and organisational elements. Six generic processes in TAM were proposed, namely, formation of TAM organisation, resource mobilisation and management, communication, conflict management, contracts management, and relationships with external organisations.

The monadelphous public report divided TAM activities into four types from contractors' perspective: essential support activities, tool time, non-essential activities, and non-maintenance execution time (Monadelphous 2015). Tool time is the physical operation has to be optimised. Essential support are the activities assist in the safe completion of tool operations, which have to be minimised. Non-essential activities are considered as waste and don't add value to the maintenance operation, such as waiting, additional transformation. Non-maintenance execution time includes the maintenance activities but is not included in the work order. The detailed activities are further classified to maintenance operation or administrative behaviors for each group.

STO Planning Handbook published by InterPlan System categorised the TAM activities in schedule to four types: safety (Permits, Testing, Gas Freeing, Neutralising, Fire and Hole Watch, etc.), inspection (Preliminary and after repairs are made), repairs (on-site and off-site, or outside shops), support (Scaffolding, Lighting, Hauling, Painting, Clean-up, etc.).

For the purpose of this study, the activities will be identified and classified by referring to the value and waste attributes.

2.4. Turnaround Maintenance

In this section, previous works related to TAM, including its definition, features and management procedures are reviewed. A summary of the challenges of VSM application in TAM is then presented.

2.4.1. The Definition of TAM

TAM is a major periodic and comprehensive routine maintenance programme when the plant is shutdown (Duffuaa and Ben Daya 2004). From the engineering point of view, TAM involves inspections, overhaul, scheduled cleaning, modification, adjustments, repairs and replacements of new parts or equipment of plant to ensure operational reliability (Duffuaa and Ben Daya 2004). The main objective of TAM is to improve the plants to ensure optimal and efficient operational performance.

From the business point of view, the successful implementation of TAM contributes to the profitability of the company (Lenahan 1999). The availability and reliability of TAM plant are critical to the success of business in the competitive global economy. Furthermore, the loss of production during plant shutdown as well as the expensive cost of turnaround itself have a huge negative impact on company profits. It should also be noted that TAM project itself is an event with a high risk of schedule slip, cost overrun due to the uncertainties, not to mention the massive resources required during TAM project. Therefore, TAM is increasingly explored as an area that can be enhanced to increase productivity and ensure competitiveness.

2.4.2. The Maintenance Process of TAM Project

Four phases of the turnaround were proposed by Lenahan (1999):

- Phase one is the initiation that covers the strategic issues and activities required to initiate the planning process.

- Phase two refers to the preparation stage, which focuses on all the detailed planning of the maintenance work. The work scope is carefully analysed and relevant resources required to complete the work are dedicated.

- Phase three is the execution stage, which emphasises on the monitoring and control of activities to make sure the maintenance work is completed on schedule and within budget.

- The last phase is the termination stage to review the performance of the completed TAM project and record lessons learned that can benefit future events.

Duffuaa and Ben Daya (2004) proposed guidelines for a structured TAM implementation in the petrochemical industry based on the four phases. The activities in the four phases are further explained and include (Ben-Daya *et al.* 2009),

- turnaround initiation and preparation is to conduct detailed planning and preparation of all aspects, include,

    - Work scope development. Work scope is the list of maintenance tasks or activities need to be conducted during TAM. TAM work consists of three categories of activities: major maintenance activities such as overhaul of large facility; small maintenance activities such as cleaning and inspection of small facilities; bulk activities such as valve overhaul or replacement, small items but with a large number. Systematic selection criteria and rules are designed to ensure only the necessary work is contained in work scope.

- WP preparation. A well planned WP is essential to efficient maintenance execution.

- Long lead time resource preparation. A special attention should be given to the procurement of material and spare parts to ensure the required sources are available when shutdown is initiated. Some of the activities, such as pre-fabricated work, special technologies that are needed, vendors' representatives, and services and utilities.

- Contractors selection. Due to the request of special skills and experienced workers, and the required number of TAM workers, it is quite common for process industries to outsource manpower supply to external contractors. It is important to select a qualified contractor to ensure project delivery.

- Site logistics planning. The site logistics organises TAM operations and shows vehicle routes and location of storage of material, location of equipment, accommodation and the effective worker mobilisation.

- Turnaround activities planning. Effective activities planning is required to ensure the right job is finished at the right time and assigned to the right workers. The planning includes the shutdown startup logic, shutdown network, startup network, critical path program, and work schedule.

- TAM organisation management. A hierarchy of TAM organisation is required to ensure the most suitable person to plan and execute TAM. TAM organisation requires the blend of plant personnel, TAM personnel, technical personnel, and contractors.

- TAM budget estimation. TAM budget includes the elements: TAM planning and management, labour from clients, contractors, spares and materials, equipment purchase and rent, accommodation, utilities, and contingencies.

- Quality plan. A quality plan is a process to ensure that the tasks are performed according to standards. It also ensures the quality of jobs are planned, executed and controlled. It includes a quality statement to guide the quality work practices and behaviors; an implementation system of the quality statement, and a quality plan for each critical job.

- Safety plan is to meet the zero accident targets which include a safety statement, a hierarchy safety communication network to specify the safety chain and clear lines of communication; and safety working routine (work permit, work environment, workers, task specification, materials and substances, and tools and equipment)

- TAM communication procedures management. In order to manage the conflicts gave rise by the diversity people involved in the maintenance process, communication plan must be planned very well to specify what, who, when, and how the communication should be organised in the most effective way.

- TAM execution. The focus of this stage is on effective monitoring and controlling the planned tasks. The steps involve finalised plan, completed event schedule, devised unexpected work, manager routine, day/night shift, shift change procedure, in control of work, cost control, daily program, daily reporting, and start of the plant.

- TAM final report. The closed TAM projects are reviewed to gather and document lessons learned. The final report needs to address TAM policy, work scope, preparation phase, planning, organisation, control of work, contractor performance, safety, quality, site logistics, communications, and recommendations for improvement. The performance and observed trends must be measured.

2.4.3. The Features of TAM Project

The execution of turnaround is a complex system in which many maintenance activities and resources interact in ways so that the action of any activity or resource can impact the execution (Bevilacqua, Ciarapica, and Giacchetta 2009). Multiple stakeholders and many activities that interact with each other including clients, maintenance contractors, suppliers, equipment, transportation, and information, are involved in TAM projects. TAM is a project environment in which the involvement of planning and control is part of the system (Bevilacqua, Ciarapica, and Giacchetta 2009). It is therefore necessary to consider flow and value generation in operation process by measuring the planning and control efficiency. Table 2-6 shows the comparisons of the features between project management and turnaround project. Some of the unique features of TAM were explained in below.

Table 2-6: The Comparisons of the Features between Project Management and Turnaround Project (adapted from (Technologies 2008))

Comparison	Project management	Turnaround management
Similarities	• Project features for one-of-a-kind, on-site production, and complexity • Classic project management techniques such as CPM/PERT are the methods applied to manage TAM project	
Differences	Scope is static, visible and is usually well defined (drawings, specifications, contracts and permits, memos, etc.). Few changes occur during execution.	Scope is dynamic, hidden and is usually loosely defined (past turnaround experience, inspection reports, operations requests and historical estimates). Many changes occur as inspections progress.
	Projects are organised around cost codes /commodities. It can be planned and scheduled well in advance of the project.	Turnarounds are work order based. Planning and scheduling cannot be finalised until the scope is approved, generally near the shutdown date.
	Generally speaking, it does not require safety permits to perform work.	Turnaround work requires extensive permits for every WP.
	Projects are measured by time in days, weeks and months. Schedules are updated either weekly or monthly and manpower, including staff requirements, usually do not change.	Turnarounds is measured by time in hours or shifts. Schedules are usually updated by every shift or daily. Manpower, including staff requirements, change during execution due to scope fluctuations.

- **Costly**

TAM project is usually very costly and requires a large number of workforces, material and supporting resources to be involved in a short duration. In addition, there is the economic loss due to non-production because of TAM. Aoudia, Belmokhtar, and Zwingelstein (2008) measured the economic impact of the maintenance management ineffectiveness, a significant financial loss has been evaluated on maintenance cost and production cost, production revenue, natural resources, and environment-related taxes.

- **Duration-driven**

TAM is a duration-driven event so that the planning of turnaround is a far more complex endeavor as all the maintenance operations and measures have to be planned to fit into a very tight schedule (generally 3-4 weeks) (Bertolini *et al.* 2009). Therefore, TAM is a high demanding project, the resources such as manpower, material, equipment, information, and technical must be carefully planned and adequately supported to avoid any inefficiency.

- **Temporary project**

The frequency of TAM is largely dependent on many variables such as the age and type of plant technology, the required level of plant reliability, and the legal requirements associated with the operation (Ghazali and Halib 2011). As such, all these variables results in unfixed plant items to be shut down and planned in an un-routine way. Every TAM is a new project has to be completed within the planned schedule. Therefore, the temporary nature has increased the risk of efficient maintenance operation (Halib, Ghazali, and Nordin 2010).

- **Dynamic project scope**

Duffuaa and Ben Daya (2004) argued that there are three major types of work in TAM. The first type of work is related to work on equipment which cannot be done unless the whole plant is shutdown. It includes activities related to inspections, preventive maintenance, corrective maintenance, and cleaning. The second type of work is related to work on equipment that does not require whole plant shutdown, but a large number of maintenance workforce and a lengthy period are required. The third type of activities is related to work on defects identified during the operation, such as the replacement or refurbishment of damaged plant parts. 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 turnaround has considerable variations and uncertainties (Levitt 2004, Lenahan 1999). This is one of the risks that can lead to turnaround delay and cost overrun.

- **Work order based project**

An essential part of TAM planning and control is the work order (WO) system. WO refers to a whole set of activities such as components replacement, purchase of new components, etc. WO system is the guideline of “what” to be involved in maintenance project (Ben-Daya *et al.* 2009). The resources required to facilitate the planning, execution, and control are included in

WO, which also gives a detailed instruction of “how” the work is carried out (Ben-Daya *et al.* 2009). Furthermore, the maintenance work included in one WO is divided into one or several work packages (WPs), which include (Duffuaa and Ben-Daya 2009) all functioning of the operation involved:

1) A clearly defined scope of the work to be done;

2) An estimation of the manpower required;

3) A clear procedure and instructions for performing the work;

4) A complete list of all tools and equipment needed;

5) All non-standard tools acquired and stored at work site;

6) A detailed list of spare parts required;

7) All necessary permits;

8) Drawings, sketches, special notes, and photographs, if needed;

9) Contact information, should question arise;

10) Coordinated vendor support etc.;

11) Schedule for execution for each type of craft;

12) Safety and environmental hazard precautions; and

13) Personal Protective Equipment needed.

The WPs are scheduled by the maintenance planners or coordinators using network analysis in order to minimise work completion time and shutdown periods (Ben-Daya *et al.* 2009). The needed information of “when” do the WPs have to get started or finished is added. Therefore, maintenance execution is the processing of WP(s) by following the scheduled procedures (Ben-Daya *et al.* 2009).

- **Extensive amounts of permits**

For safety concern, the permit-to-work system is widely adopted in TAM project to protect workers, plant equipment, and the environment from any accidents. The permit system is the principal measure to ensure that work other than routine operations is properly controlled and co-ordinated (Matsuoka and Muraki 2002). The work permit must be obtained prior to execution of any jobs.

- **Multi-level schedule structure**

According to Bevilacqua, Ciarapica, and Giacchetta (2009) and Bevilacqua *et al.* (2005), a typical TAM project consists of 4 to 5 levels of operation based on the functional logic and the size of the project. A major turnaround project, includes the maintenance work to be conducted in several independent trains (which is categorised as the first level). The second level (i.e. a more detailed level) divides the work into plant units (e.g., compressor or turbine) which need to be overhauled or replaced in each train. The third level further divides the work into a more defined system unit. For instance, spool removal is a detailed maintenance package in the compressor overhaul. Maintenance batches and associated maintenance activities are developed at level four and five respectively (as shown in Figure 2-6).

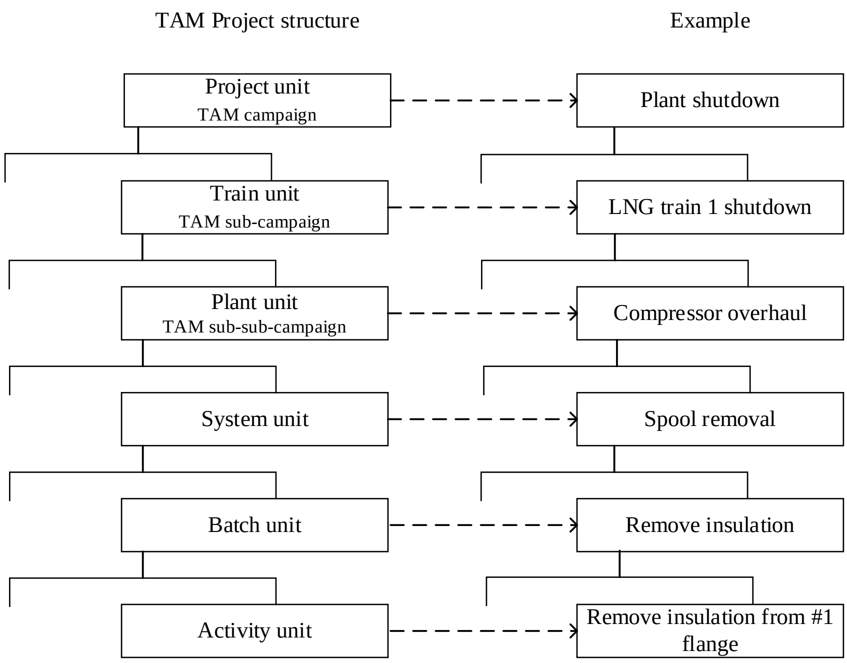

Figure 2-6: The TAM Project Structure

2.4.4. Research on TAM

Over the past few decades, strategies to improve TAM performance have progressed from the exploration of TAM processes to more sophisticated strategies. Ever since Duffuaa and Ben Daya (2004) outlined the guidelines for a structured approach for managing TAM in the petrochemical industry, many studies have been conducted.

Hadidi and Khater (2015) proposed an analytic hierarchy process (AHP) model to select contractors based on safety criteria. It suggested contractor selection should base on work performed in the past, workers' expertise, and technical planning along with HSE plan. It also addressed the necessity to integrate contractors with plant safety procedures.

Obiajunwa (2012) established a framework to evaluate the performance of TAM projects. Success measurement criteria for TAM project was developed base on three components: management success (project management efficiency), the perception of stakeholders (perception of uses), and resultant benefits to the business (benefits to the organisation accruable). It emphasised the importance management to the success of a TAM project.

Cui, Hayakawa, and Obiajunwa (2013) identified the management skills/knowledge required for the successful management of TAM projects. By considering the inherent difference with generic projects, it identified skills relevant to successful TAM management, which include, leadership skills, conflict resolution skills, planning skills, organisational skills, time management skills, negotiation skills, forecasting skills, and motivation skills, management support building skills, resource allocation skills, communication/presentation skills, decision-making skills, health, safety and environment management skill, use of computer technology, technical skill/knowledge, control skills, contract management skill, quality management skill/knowledge, risk management skills, administrative skills, human resources management skills, budgeting and budgetary control, cost management, supervision of others.

Another link in this chain of progress has recently been added by the introduction of relative theories, methods, and technologies to TAM project. The integration has been suggested as a new vision for process efficiency.

Amaran *et al.* (2016) developed mathematical models to handle the uncertainty in turnaround duration. They investigated the turnaround planning problem under uncertainty over a medium-term time horizon. The timezone allows them to measure the impact on manpower and building down-stream inventory.

Bevilacqua, Ciarapica, and Giacchetta (2009) applied the theory of constraints and risk assessment to the turnaround process. This study addressed the applicability and necessity of the risk analysis process to examine and evaluate the schedule and cost features of a turnaround project.

Halib, Ghazali, and Nordin (2010) proposed an analytic framework for examining the organisational dimensions of the plant turnaround by describing six core generic processes through the general three concepts of institution and organisation, namely, rules, roles, and groups. The generic processes include the formation of turnaround maintenance organisation, resource mobilisation and management, communication, conflict management, contracts management, and relationships with external organisations.

Söderholm and Norrbin (2013) applied a risk-based dependability approach to link maintenance performance measurement and management. The proposed risk-based dependability approach enables critical availability goals are communicated with and involve top management.

2.5. Action Plan Development and Implementation

In this section, firstly, previous approaches for Action Plan development and implementation are reviewed and summarised including their advantages and disadvantages. Then, a new approach (i.e. 4D BIM technique) is introduced which includes the definitions of BIM and 4D BIM, and their histories and functions. Finally, the application of 4D BIM in building and infrastructure projects are reviewed which is helpful in guiding 4D BIM implementation in TAM projects.

2.5.1. Previous Approaches for Action Plan Development and Implementation

The Step of Action Plan development and implementation is critical to transform current state VSM to future state VSM. Current approaches for Action Plan development and implementation can be classified into the following two categories: (1) Workshop-based approaches; and (2) Simulation-based approaches. Each of them is explained in detail as follows.

(1) Workshop-based approaches

This type of approaches is widely used in developing and implementing Action Plans, especially for those projects with small and medium scale size (Chen *et al.* 2010). The development of an Action Plan is usually carried out by conducting workshop-based interview with the participants in the processes. Regular workshops that are conducted weekly or monthly provide opportunities for project participants to share and update the status of the proposed Action Plans. The main advantage of this type of approaches is easy implementation, however, a number of drawbacks need to be highlighted: (1) Workshop participants spend most of their time trying to understand the process information rather than using the information to address “What-If” questions; (2) The Action Plan is static and also not interactive; and (3) Views are inappropriate for group use, such as the Gantt chart which only provides an overall context, but is not adequate for any group tasks.

(2) Simulation-based approaches

This type of approaches is widely used in the manufacturing and construction industry. In order to investigate the effect of the initiatives before proceeding to real world application, simulation-based approaches such as Discrete Event Simulation (DES) have been proven as one of most efficient ways (Gurumurthy and Kodali 2011). McDonald *et al.* (2002) are the researchers who firstly apply the simulation method in VSM. Abdulmalek and Rajgopal (2007) illustrated the VSM benefits in reducing lead-time and lowing work-in-process inventory by developing a DES model. Gurumurthy and Kodali (2011) has reviewed 13 papers describing the application of DES in VSM application. It concluded that DES is a tool that more prevalent in manufacturing industry. Similar research can be also found in Ali *et al.* (2015), Alvandi *et al.* (2016), Andrade *et al.* (2016), Atieh *et al.* (2016), Aziz *et al.* (2017), Bal *et al.* (2017), Doğan and Unutulmaz (2016), Helleno *et al.* (2015), and Schmidtke *et al.* (2014). However, this kind of simulation-based approaches mainly focuses on measuring the impact of variability and dynamic changes in production system and their impact on lean implementation. Solding and Gullander (2009) summarised the weaknesses with simulation, including time-consuming and difficulty of getting right amount of data in right format.

2.5.2. BIM and 4D BIM

BIM is emerging as a method of creating, sharing, exchanging and managing the information throughout project life cycle among all stakeholders (Wang *et al.* 2015).The term "BIM" has two meanings, according to Eastman who introduced BIM into AEC/FM domain, one means Building Information Model, another is Building Information Modelling. The former refers to the 3D building models, while the later means the process of creating and processing 3D building models (Eastman *et al.* 2011). Currently, the widely accepted definition for BIM is from the National Building Information Model Standard Project Committee (NBIMS 2015), which defines BIM as:

"*BIM is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.*"

In general, BIM can be treated as (1) a number of tools that improve work productivity. For instance, design managers can automatically detect clashes among different design disciplines by using BIM tools; (2) a central database that stores the up-to-date project life-cycle data; and (3) a central platform that facilitates collaboration among project stakeholders at different phases (i.e. plan, design, construction, and operation phases).

The underlying concept of BIM is not attributed to one person but is a rich history of innovation from multiple countries such as the United States of America and Northern Europe. Back to 1970s, Computer-Aided Design Drawings (CADD) was invented and replaced the hand drawings, which significantly improve the design productivity (Emery 2008, Autodesk 2012). However, when printing the CADD on paper, they were still flat images in two dimensions. The three-dimensional (3D) drawing software became available in the 1990s (Emery 2008). Compared with CADD, they were more advance and could conduct object-oriented design (i.e. treating building elements as 3D objects). However, associated information about each component could not be accommodated. Throughout the past decade, these 3D CAD tools have been significantly improved (Emery 2008, Autodesk 2012). Building elements cannot only be treated as an object but also directly tied to an "intelligent" database. For instance, when a door is designed in 3D, it will be automatically shown in other building views, such as floor plans, elevations, and sections. In addition, if the door is moved or deleted, the door schedule will change instantly. However, these 3D CAD tools remain rooted to building graphics, built on graphics-based CAD foundations, and as a result are not fully optimised for creating and managing information about a building (Emery 2008, Autodesk 2012).

The BIM concept is developed on the top of these 3D CAD tools, and extends the software focus from design stage to the whole project life-cycle including construction, commissioning, and operation and maintenance. In addition, by storing and managing building information as databases, BIM can capture, manage, and present data in appropriate ways for data exchange (Autodesk 2012). The term "Building Information Model" was firstly introduced in a paper written by G.A. Van Nederveen and F. Tolman in 1992 (Eastman *et al.* 2011, Emery 2008). At that time, few software could efficiently support the concept due to the hardware limitation. In 2002, after acquiring Revit, Autodesk introduced a new term "Building Information Modelling" to the building industry and described it as we know now (Autodesk 2012). It should be noted that Charles Eastman proposed a similar concept named "Building Description System" in 1975 (Eastman *et al.* 2011).

A 4D BIM model results from the linking of 3D model to the fourth dimension of time. In the 4D model, the temporal and spatial aspects of the project are inextricably linked, as they are during the actual construction process. In project shaping stage, 4D BIM is useful in communicating and validating construction plans and processes, while during construction phase, they are helpful in identifying errors in the logic of the schedule, potential time-space conflicts, and accessibility issues. When integrating with other technologies such as Radio Frequency Identification (RFID) and Laser Scanning, BIM can produce greater effectiveness (Fang *et al.* 2016). For instance, Wang *et al.* (2015) developed a real-time construction quality control by integrating BIM and laser scanning. Turkan *et al.* (2012) applied 4D BIM together with 3D sensing technologies for automated construction progress tracking.

2.5.3. 4D BIM Application in Building and Infrastructure Projects

In recent years, 4D BIM has been largely implemented on building and infrastructure projects. The projects in design and construction phases are both benefited from using 4D BIM techniques in various aspects. This section will review building and infrastructure projects which leverage 4D BIM techniques in order to understand current trend of implementing 4D BIM. It will help identify right strategies for using 4D BIM in TAM projects.

4D BIM research for building projects can be roughly categorised into design phases and construction phases depended on when 4D BIM is implemented. With regard to design phase, most of 4D BIM techniques are used for improving collaboration between stakeholders. For example, Chaves *et al.* (2015) demonstrated the process of leveraging 4D BIM for a retrofit project. A 4D BIM model was built based on a 3D model and a works schedule; in result, disruptions were identified in advance and what-if scenarios were created to explore feasible solutions. More specifically, the 4D model was presented to stakeholders. A set of categorised disruptions were defined, and potential disruptions were highlighted and characterised in 4D model which helps better understanding of disruptions among stakeholders. In addition, 4D BIM simulations were adopted to create what-if scenarios for stakeholders. These scenarios help seek a solution for minimising or avoiding disruptions during the retrofit process. Apart from improving collaboration to avoid disruptions, some research focuses on building an algorithm for automatically assessing constructability. The algorithm may check and suggest corrections of the design to reduce possible disruptions. To accomplish the abovementioned idea, the factors defined in the research are embedded in 4D BIM models. These models are served as a data repository for assessment process. As a result, constructability of the design can be calculated based on spatial relationship and these parameters in 4D BIM models (Zhang *et al.* 2016).

In terms of construction phases, most research studies contribute to target-specific tasks such as monitoring progress, construction safety, or supply chain management. To start with, Kim, Son, and Kim (2013) proposed a method for monitoring construction progress by aligning site data and BIM model. These site data captured by remote-sensing technology are extracted and matched to elements in BIM model automatically. After that, an automatic revision process based on topological relationship involves to detect and correct any logical inconsistencies. Therefore, this aligning and correcting process increases the accuracy of monitoring progress. Similar concept has been conducted in other research with different methodology. For instance, research from Han and Golparvar-Fard (2015) proposed an appearance-based material classification method to align 4D BIM models and point cloud models which is generated from site photos. The algorithm developed in this research recognises the material in daily construction photo logs and attaches the material on 4D BIM models. As a result, construction progress can be monitored in operational level with high accuracy. On the other hand, Tuttas *et al.* (2017) suggested that a precise point cloud model can be built by using Unmanned Aerial Vehicle (UAV). The procedure proposed by their research successfully reduced the deviations of point cloud models to 3-5 cm which is acceptable for progress monitoring of buildings. Site managers may compare as-planned 4D BIM models and 3D point cloud models to identify current status on site. In short, although there may be some practical limitations for adopting 4D BIM technologies for monitoring construction progress in field, research studies have proved that 4D BIM technologies can benefit progress monitoring on site.

For health and safety issues in construction phase, Ganah and John (2017) conducted a systematic literature review and a questionnaire survey to layout the framework of BIM usage in health and safety planning. It concluded that a single health and safety guide incorporated in BIM-enabled visualisation is a feasible solution for building a holistic environment where health and safety issues can be communicated. Furthermore, the integration of planning software, BIM platform, and knowledge database in the proposed framework helps identify health and safety issues which are not easy to be discovered without the aid of visualisation. Azhar (2017) also states that visualisation plays an important role for recognising possible hazards before construction proceeds. Three case studies were investigated by visualising 4D BIM models with Virtual Reality technology which effectively identify safety issues compared to the 2D static drawings. This immersive environment is found to be effective for health and safety education or training as well. On the other hand, some research aims to develop a rule-based engine to automatically detect safety hazards and suggest preventive measures. The fall protection algorithm developed in the research automatically check 4D BIM models phase by phase and add guardrail in different scenarios, such as staircases, slab edges, slab openings, and wall openings. Even though only fall related hazards are considered in this research, it shows the potential of 4D BIM technique for early scheduling of safety planning (Zhang *et al.* 2013).

Recently, research studies focus on Construction Supply Chain Management (CSCM) which can benefit from 4D BIM and Geographic Information Sciences (GIS) due to the demand of highly integrated information. Deng and Cheng (2016) developed a framework to illustrate the usage of 4D BIM and GIS information to solve the major problems in CSCM which include the selection of suppliers, quantity of deliveries, and allocation fee. By calculating the data from BIM and GIS in mathematical models, decisions or business strategies with lower cost could be found which largely improves the performance of CSCM. It is proved that the integrated 4D BIM and GIS information is capable of providing deep understanding and solutions for the managing problems in CSCM.

In terms of infrastructure projects, applications of 4D BIM are similar to the usages in building projects. For example, in the preconstruction stage, both road projects in Australia and China conducted quantity take-offs and clash detection with 4D BIM techniques which have been widely implemented in building projects. These applications provide accuracy and currency of visualised data which serves the needs of subcontractors. Furthermore, regarding infrastructure-specific applications, traffic impacts can be simulated to predict the flow on highway which may avoid potential congestion in advance. These innovative uses show that 4D BIM is a practical technique for infrastructure projects in preconstruction stage (Chong *et al.* 2016).

There are more applications about visualising 4D BIM models in construction stage for infrastructure projects. According to Chong *et al.* (2016), earthwork areas can be clearly shown in 4D BIM models. Both design and construction team can clearly aware of the excavated area with tablets on site which results in a reduced information gap among stakeholders. This approach not only improve the quality of collaboration, but also help monitor construction progress. On the other hand, due to the large scale of infrastructure projects, the number of monitoring progress with UAVs has exponentially grown. A visually as-built model can be built with low cost in a small period of time. The model can be compared to 4D BIM models to understand the current progress without complex manipulation (Ham *et al.* 2016).

In summary, 4D BIM techniques have been widely adopted in various approaches in both building and infrastructure projects. In addition, the applications can benefit the projects from design to construction stage. Therefore, it is worthwhile to leverage 4D BIM technique in a TAM project to transform current state VSM to future state VSM.

2.6. Summary

This chapter investigated the theoretical background of this research. The lean philosophy is the foundation of this research. The theory of VSM was applied to improve the process efficiency of TAM projects in this research. However, the framework of VSM application should be enhanced in order to take the unique features of TAM projects into consideration. First, the differences of VSM application in difference environments should be taken into consideration. The key factors of efficient VSM application should be investigated by reviewing VSM application in different sectors. The theoretical background was supported by lean production theories, the definition of value and waste is one of the key theories have to be investigated. In addition, the definition and features of TAM were analysed. Finally, the application of 4D BIM was analysed based on a systems approach.

The research would be carried out on two parts, which were framework development (Chapter 4, 5, and 6) and validation (Chapter 7). The results would contribute to the development of lean philosophy in project-based process by answering how the theory and procedures of VSM should adapt to TAM projects (research objective 1, 2, and 3). In addition, the application of 4D BIM facilitated VSM framework would be useful for the evolving of evaluation method (research objective 4).

Chapter 3: Research Methodology

Research methodology is a scientific investigation process which provides principles and procedural framework for carrying out research (Fellows and Liu 2015). It is the overall strategies to achieve the research aim and objectives (Sutrisna 2009). Research methods are the tools used to achieve the aim and objectives (Sutrisna 2009). This chapter presents the discussion of research philosophy, method selection, and data collection and analysis for each objective in this study.

3.1. Research Philosophy

3.1.1. Paradigm

Guba (1990) defined paradigm as a basic set of beliefs that guide action. Paradigms deal with principles, or ultimates (Denzin and Lincoln 2011). Denzin and Lincoln (2008) (p. 245) suggested paradigms as basic belief systems based on ontological, epistemological, and methodological assumptions. They are the philosophical stances of the research. Ontology discusses the beliefs of the nature of reality and humanity, epistemology is the theory of knowledge that informs the research, and methodology focuses on how the knowledge can be acquired. A comprehensive consideration of ontology, epistemology, and methodology is a central feature of social science research (Guba and Lincoln 1994).

Ontology is the study of reality (Crotty 1998). Blaikie defined ontology as the study of "*claims and assumptions that are made about the nature of social reality, claims about what exists, what it looks like, what units make it up and how these units interact with each other*" (Guba and Lincoln 1994, p.10). The ontological position of a research is the investigation of the nature of the reality. The popular example of ontological positions includes objectivism vs. constructivism (Sutrisna 2009). Objectivism claims that the empirical fact is the objective reality which exists independently from personal ideas or thoughts, so that everyone experiences the same way to the reality (Sutrisna 2009, Crotty 1998). Constructivism claims that the world is continually being constructed, interpreted, and accomplished by people in their interactions with each other and with wider social society, so that everyone constructs the reality differently (Sutrisna 2009, Marczyk, DeMatteo, and Festinger 2005).

Epistemology concerns the claim of "*what is assumed to exist can be known by the knower or to-be-knower"* (Guba and Lincoln 1994). It is defined as "*the theory of knowledge embedded in the theoretical perspective and thereby in the methodology*" (Crotty 1998) (p.3). It deals with what it means to know of the nature, sources, and processes of knowledge and knowing that to be created, acquired and communicated (Cohen, Manion, and Morrison 2013).

Epistemology is the view of how one acquires knowledge. Epistemology looks at especially the methods and the possible ways of gaining knowledge in the assumed reality (Sutrisna 2009). The two broad epistemological positions are positivism vs. interpretivism (Sutrisna 2009). Positivism advocates the application of methods to observe, study the reality and discover the truth according to the same principles of natural science (Sutrisna 2009, Bryman 1984). Interpretivism claims that the reality separates from the observers/researchers, the truth of the reality is constructed individually and interpreted from their own viewpoint (Sutrisna 2009).

Objectivism is the basis of positivist to understand reality with the focus on experiencing only one reality by all observers/researchers. Constructivism is the basis of interpretivist to understand reality with different viewpoints. It is argued that the philosophical view may be divided into two dimensions: one with objectivist ontology and positivist epistemology, another with constructivist ontology and interpretivist epistemology.

3.1.2. Deductive and Inductive research

The next level of research methodology is the discussion on the reasoning of research (Sutrisna 2009). It refers to the logic of the research, which focuses on exploring the role of existing body of knowledge gathered from the literature study, the way researchers utilise the data collection and subsequent data analysis (Sutrisna 2009). Deductive and inductive research are the two ways of reasoning. The logic of deductive research is composing hypothesis based on current body of knowledge (one objective truth), followed by data collection and analysis to test the hypothesis, whilst the logic of inductive research starts by conducting data collection and analysis to come up with findings, then using the current body of knowledge to inform the data analysis when researchers see appropriate (Sutrisna 2009).

3.1.3. Qualitative and quantitative research

The research methodology used in social science can generally be divided into qualitative and quantitative. Quantitative approaches follow the ontological position of objectivism. They are based on the positivistic ideal – an idea of independently existing reality that can be observed as it is. Quantitative methodology is routinely described as an approach to test theories deductively, a focus on gathering factual data, carrying on controlled inquiry against bias, and quantifying objective explanation (Steckler *et al.* 1992). Researchers are verification and outcome-oriented, and the results are viewed as generalisable, replicable and capable of isolation from reality (Slevitch 2011, Tuli 2011). Quantitative research is usually designed under experimental conditions to test theories. It is conducted in an attempt to answer questions such as why something happens, what causes some events, or under what conditions an event does occur (Hughes 2012).

Qualitative methodology is inductive. It is based on constructivism and interpretivism (Steckler *et al.* 1992). Qualitative methods focus on investigating the quality of phenomena, taking into account the interactions between reality and researchers, and explaining the phenomena from the viewpoint of participants. The data used in qualitative research are subjective as the events are understood and explained when researchers immersed in the context. Qualitative approaches are discovery and process oriented; the results are less concerned with generalisability and replicability (Tolley *et al.* 2016, Tuli 2011). Qualitative research is usually used to suggest possible relationships, effects and dynamic processes (Hughes 2012).

Mixed-methods are the combination of both qualitative and quantitative research approaches. It involves the mixed use of qualitative and quantitative methods concurrently or subsequently in the study of the same phenomenon (Creswell and Clark 2007).

This study aims to developing an Enhanced-VSM framework for improving the process efficiency of TAM projects. According to the aim of this study, the ontology of this research is to find the links between VSM and turnaround projects in oil and gas industry. The epistemological part of this research is to define the process of exploring and validating the links between them.

In accordance with the research objectives of this study, the methods of literature review, focus group study, interview, and case study are used. The process of data collection and analysis, results testing and interpretation involve quantitative analysis, for example, a structured literature review of the state-of-the-art of VSM application in five sectors to identify the critical factors of VSM implementation. Qualitative explanation of the findings is also conducted. The process also involves qualitative evidence, for example, validation of the developed standardised VA and NVA framework. The integration of both types of methodologies are also involved. For example, the validation of the proposed enhanced-VSM framework involves both case study and interview.

The descriptions of the process of data collection and analysis that are related to the four research objectives outlined in Section 1.3 are introduced in the following four sections respectively.

3.2. Research Method for Objective 1

Objective 1 is to obtain an in-depth understanding of the VSM applications in different sectors. Therefore, a comprehensive literature review was conducted to map the development and implementation of VSM. Figure 3.1 shows the procedures for data collection and analysis.

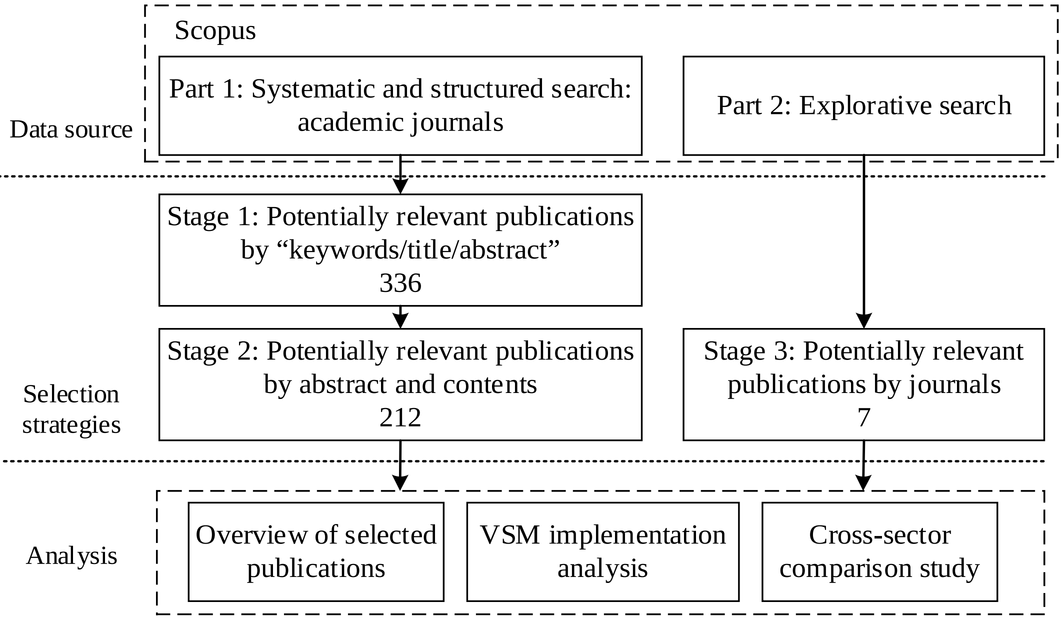

Figure 3-1: Data Selection and Analysis Process

3.2.1. Data Sources and Selection Strategy

In order to identify relevant studies, two search criteria were established for paper retrieval. Firstly, only academic journals were selected for review. Book reviews, editorials, and papers in conference proceedings were eliminated to ensure that all retrieved papers could be investigated using an identical analytical construct in terms of research aims and methodologies. The academic databases: Scopus, which is the world's largest multidisciplinary dataset of peer-reviewed research literature, was used to identify relevant publications. Secondly, the scope of publication search was scaled down to a time span of 1999–12/2016. This timeframe was selected because the concept of VSM was proposed in Rother and Shook (1999) which led to further VSM development and implementation. To acquire a more elaborated understanding of VSM related research, the search was further refined by three stages:

- Stage 1. A document search was conducted using "keywords/title/abstract". Two sets of keywords about lean and value stream mapping: ("lean" OR "lean thinking") AND ("value stream mapping" OR "value stream management" OR "value stream analysis" OR "value stream process") were used in the retrieval process. These sets of keywords can be used to capture relevant variations of a word. A total of 336 articles were initially retrieved. Despite the rigorous search rule, some retrieved publications appeared to be less relevant.

- Stage 2. A brief review of the abstracts and contents of these publications identified in stage 1 was conducted to exclude less relevant papers. A total of 212 publications which did not contain the aforementioned keywords in titles and abstracts were excluded. For example, studies, such as Vlachos and Bogdanovic (2013) and Bogdanovic (2013) were excluded because they didn't employ the concept of VSM.

- Stage 3. A manual search was adopted to include the possibly overlooked VSM research papers archived by the search engine. Two VSM related papers from the International Journal of Logistics Research and Application published between 1999 and 2008 were identified. Similarly, one paper published in Business Process Management Journal and four papers published in International Journal of Advanced Manufacturing during the study period were identified and included.

3.2.2. Data Extraction and Analysis

After the three-stage search, a total of 131 publications were identified for further content analysis. Table 3-1 shows the content of the analysis. VSM is an iterative process which usually includes selecting the product family, identifying the current state map, analysing waste and mapping the future state (Chen, Li, and Shady 2010; Jiménez *et al.* 2012; Lacerda, Xambre, and Alvelos 2016). The process has three critical elements, including the current state VSM which shows how both materials and information flow in the current system, the identification of waste (e.g. waiting, inventory, transportation, and defects) and the future state VSM which shows the ideal production system. As such, the implementation of VSM in the publications was reviewed and analysed from four perspectives: the metrics applied for current state analysis, the tools used for future state improvement, the benefits achieved by the implementation (i.e. waste identification and quantification), and the critical success factors of VSM implementation.

Table 3-1: The Code of Content Analysis

Code	Definition of the code
Year of publication	The distribution of selected articles by years
Journals of articles	The journals of the selected articles get published

Code	Definition of the code
Sectors of articles	The distribution of selected publications by sectors
Lean metrics for current state analysis	The lean metrics the articles have adopted
Lean techniques for future state improvement	The lean tools/techniques have been used in selected articles
The benefits of VSM implementation	The benefits have reported
The CSFs for effective VSM implementation	The CSFs have reported

3.3. Research Method for Objective 2

Objective 2 is to develop a standardised classification system of VA and NVA activities in TAM projects. Figure 3-2 Figure 1 shows the research design for developing the standardised classification system. Firstly, enlightened by the discussions in the literature review, a draft classification system was developed by elaborating the definitions and classifications related to lean application in TAM projects. As a result of this analysis, a draft classification system that can be used in TAM projects for lean applications was proposed by considering the specific characteristics of TAM projects. After the initial development, the classification system was then refined in two focus group studies. The refined classification system was validated by conducting interviews with the focus group experts in terms of the ontology effectiveness. Finally, a sample case was used to evaluate the reliability of the classification system. Each method is discussed in details in the following sections.

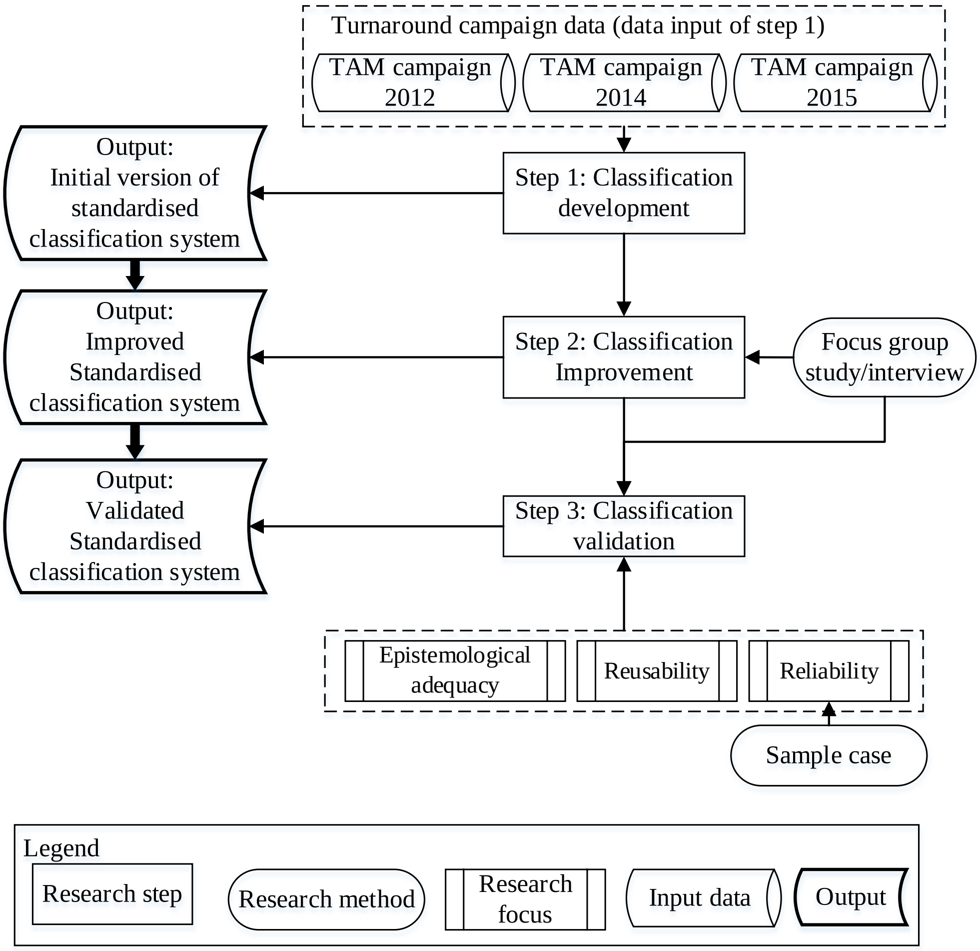

Figure 3-2: Research Methods for Developing Standardised VA and NVA Classification System

3.3.1. Classification Development

There is no standardised VA and NVA definition system for TAM project at the time of the study. Therefore, the definition of the principles of VA, NVA, and waste in TAM project was discussed at first. According to the literature review in Sections 2.3.1, 2.3.2 and 2.3.3, the basic customer-centreed value definition is the foundation of lean implementation in maintenance projects. The concepts were refined with the specifics of both project management and TAM management considerations. Specifically, Han, Lee, and Pena-Mora (2011) and Mao and Zhang (2008) were referred to for the definition as their work were considered as the most relevant to this study because: (1) the focus of the customer-centred value definition is on investigating efficiency of process management in TAM project, rather than simply analysing physical transformation; (2) the focus of value stream recognition is on analysing trade crews contribution in process, rather than classifying production actions of product production.

For the purpose of this study, which is to category the maintenance activities according to the specified value and waste, the development of the classification system was based on the disciplines of tool time proposed by Monadelphous (2015), as well as the four types of categories proposed in STO planning Handbook considering the functionalities of maintenance activities.

In addition, activities conducted during the turnaround execution of three TAM projects in oil and gas industry between 2012 and 2015 were analysed to finalise the list (as shown in Table 3-2). A total of 7808 operation activities from three TAM projects were identified and analysed. The main work scope involved within each project includes main facilities in Gas plant. The activities in TAM projects were categorised along two dimensions: context and effort. As shown in Table 3-3, the context dimension divides the activities into major domains: tool operation, safety, quality inspection, and support. Within each context, the effort dimension classifies activities according to functionalities of the operator.

A standardised classification framework was then proposed by considering both the redefined value and waste as well as the categorised activities. Details of the framework development are introduced in Chapter 5.

Table 3-2: The Cases Used for Activity Development

TAM project	Input data	Number of activities during execution	Main work scope involved	Man-hour consumed (hour)	Year
Gas Plant Major Turnaround	• Project operation schedule • Documents for each Workpackage	2,468	• Turbine hot gas path inspection • Compressor bearing & seal inspection • Compressor major inspection • Valve repairs & replacement • Vessel inspections	56007	2015
Gas plant major turnaround		3204	• Turbine major inspection • Statutory vessel inspection • Bearing & seal inspection • Tray modification • Valve overhauls, upgrades and replacement • Compressor major inspection	62354	2014
Gas plant major turnaround		2135	• Compressor major overhaul • Bearing & seal inspection • Turbine and compressor inspections • Line and vessel repairs • Valves maintenance	51338	2012

Table 3-3: The Categories of Activities in TAM Projects

Context	Effort
Tool operation	• On-site: ➢ Physical engineering operation conducted by: Electrician Instrument/Electrical Technician HVAC technician Lagger/insulator Mechanical fitter Operator Welder Boilermaker Gas fitter/plumber Service technician General service operator Rotating mechanical ➢ Operation sign on/off conducted by supervisor ➢ Operation update and turnover conducted by supervisor ➢ WPs sign in/off by Superintendant ➢ Daily progress update by scheduler • Off-site: ➢ Physical engineering operation conducted by: Painter Blaster Welder Valve vendor
Safety check	• Permits sign on/off conducted by supervisor • Permit record conducted by supervisor • HSE data collection and record conducted by inspector
Quality Inspection	• QA/QC conducted by inspector (welding, tube) • QA/QC sign on/off conducted by supervisor

Context	Effort
	• QA/QC conducted by quality measuring instrument (QMI) technician • Testing conducted by inspector (cathodic protection, condition monitoring, crane, electrical, lifting equipment, protected coating, rotating, etc.) • Testing sign in/off conducted by supervisor • Testing record conducted by supervisor
Support	• Scaffold erection, modification, and dismantlement activities conducted by ➢ Scaffolder • Lifting, rope access or rig up activities conducted by ➢ Rigger ➢ Dogman ➢ Crane operator • Store management relevant activities which conducted by Materials officer/storeman • All the communication conducted by Communication technician • Logistics for labour and resource delivery activities conducted by ➢ Bus driver ➢ Truck driver ➢ Fork lift driver • Electronic data compiling conducted by administrator

3.3.2. Classification Improvement

In order to improve the proposed classification system, focus-group study was adopted. Focus group is a commonly adopted qualitative research method in the social sciences (Merton and Kendall 1946). Focus group is a controlled group discussion on specific tops in a defined environment (Krueger and Casey 2009, Leung, Yu, and Chan 2013). It is particularly used to obtain results from the interactive group discussion rather than from individuals (Vaughn *et al.* 1996).

This study is to develop the specific VA and NVA definition and classification for TAM projects. The process of such development involved examining the opinions of stakeholders. Therefore, this study selected a focus group to evaluate and validate the developed classification system. Yu and Leung (2015) summarised that the number of participants involved in a focus group vary from two, three, four to six (mini-group), seven to ten (small), to eleven-twenty (super-group) (Cooper and Schindler 2006). Focus group allows participants interaction to exam and challenge the views backed by individual participant to avoid the negative impact of individual bias (Morgan 1997, Fisher 2011).

Smithson (2000) and Krueger and Casey (2014) pointed out that one of the limitations conducting focus group is the possible negative impact of moderator bias and dominant voices. Myers (1998) argued that in order to minimise this type of impact, the moderator should play as assistant, not a director to lead the group discussion. The moderator should be the one who is familiar with the topics and tones of the group discussion, and indicates the issues and problems which have to be discussed and addressed within the specified scope and topics (Sim 1998, Kidd and Parshall 2000).

In this study, three separate focus group studies were conducted to explore three specific issues based on participants' experience, aiming to address three questions:

- Are there any missing activities can be added in and/or misunderstanding of the activities in the classification system?
- Is the taxonomy of the classification system correct to reflect TAM operations?
- Is the classification system effective to classify NA and NVA activities in TAM operation?

Participants Selection

Two rules of participant selection were set to ensure data reliability. Participants were selected if (1) they have 10+ years work experience in planning, delivering, and managing TAM projects in the oil and gas industry; and (2) they have participated several TAM projects in the recent 3 years.

According to the suggested optimum group sizes (6-12 participants) (Krueger and Casey 2014), there were 10 practitioners in total, including two TAM schedule planners, two WPs designers, and one production managers who was in charge of the planning and control of permit system, one TAM superintendent who had specialised expertise in process management, one site manager specialised in maintenance operation, one off-site component maintenance vendor, and two lean experts from Curtin University. As shown in Table 3-4, the participants had experience in various aspects of TAM projects. The selected participants are the members in the three focus group studies.

Table 3-4: Profile of the 10 Participants and Their Contribution

No.	participants	Expertise
1	TAM schedule planner from client	Schedule planning and control
2	TAM schedule planner from client	schedule planning and control
3	WPs designer from client	WPs design and management
4	WPs designer from client	WPs design and management
5	Production manager from client	Permit system planning and control
6	TAM superintendent from client	Process management
7	Site manager from contractor	Maintenance operation
8	Maintenance vendor	Off-site component maintenance
9	Lean research from Curtin University	Lean production knowledge
10	Lean research from Curtin University	Lean application knowledge

Data collection

At the beginning of the focus group studies, the author, as the moderator, introduced the purpose of the focus group study, followed by the explanation of the ground rules of equality of speech (participants were encouraged to freely provide any comments, suggestions, objections, and doubts) and confidentiality arrangement (Beasley and Jenkins 2003). Before the start of the discussion, all the participants made a brief self-introduction of their current roles in TAM projects. They were then asked about perceptions and opinions of the draft framework. Both discussions followed a predefined semi-structured framework and schedule to ensure that effective information could be collected and new ideas could be brought up.

To ensure the validity of the information provided, discussions were reviewed and summarised based on the data from both recorded audiotapes and the immediate notes taken by the moderator during the discussion. Audiotapes enabled the discussions to be reviewed in details at any time and the notes highlighted the key points provided by participants during the discussion.

3.3.3. Classification Validation

The criteria proposed by El-Diraby and Kashif (2005) for validating ontology effectiveness and representation were used in this research. This method was also adopted by Macarulla *et al.* (2012) to validate defects classification in construction. The validation was conducted by capturing opinions of experts regarding the (1) epistemological adequacy, (2) reusability, and (3) reliability.

According to the research methodologies designed by El-Diraby and Kashif (2005), a structured interview was chosen as the principal evaluation method in the focus group to capture opinions of experts. 6 interviewees were selected out of the 10 experts, including one TAM manager, one TAM superintendent, one site manager from the contractor, one maintenance vendor, one schedule planner from TAM planning office, and one lean researcher.

- Epistemological adequacy. Epistemological adequacy refers to the extent to which the classification resembles the cognitive sentences. Four questions were proposed to address epistemological clarity, intuitiveness, relevance and completeness (Table 3-5). Experts were asked to rank from 1 to 6 of the extent (with 6 being the most favorable) in each question. All the concepts in the improved framework were evaluated collectively for addressing epistemological adequacy.

Table 3-5: Evaluation Criteria for Epistemological Adequacy (El-Diraby and Kashif 2005, Macarulla *et al.* 2012)

Criteria	Question	Ranking rule
Epistemological clarity	Q1: Do all concepts and relations in the classification system have clear and unequivocal meaning?	1, 2, 3, 4, 5, 6
Epistemological intuitiveness	Q2: Does the classification system provide a vocabulary that matches the intuition of the experts?	1, 2, 3, 4, 5, 6
Epistemological relevance	Q3: Are all the concepts in the taxonomy relevant for the domain?	1, 2, 3, 4, 5, 6
Epistemological completeness	Q4: Does the classification system cover all relevant concepts that may be relevant to any task, activities?	1, 2, 3, 4, 5, 6

- Reusability. Reusability refers to the extent to which the classification system can be reused to classify VA and NVA in other situations. The same ranking rule was applied (Table 3-6).

Table 3-6: Evaluation Criteria for Reusability (El-Diraby and Kashif 2005, Macarulla *et al.* 2012)

Criteria	Question	Ranking rule
Classification reusability	Q5: Is the classification usable for all types of TAM project in oil and gas industry?	1, 2, 3, 4, 5, 6
Domain reusability	Q6: Is the classification dependent on certain types of domains?	1, 2, 3, 4, 5, 6

- Reliability. In order to evaluate the reliability of the classification system, a two-step evaluation procedure was adopted by using the interview. In step one, the six interviewees were asked to classify the 20 randomly selected activities according to the proposed classification system. This step offered an intuitive guidance for the interviewees to understand the classification scheme. The interviewees were required to provide comments on the accuracy of the terms and the appropriateness of the categories in the classification system. At the second step, Cohen (1968)'s Kappa was used to measure the inter-rater reliability. Kappa is the indicator which shows the extent of difference between the observed agreement and the expected agreement. It has been argued in the literature that values above .75 indicate excellent agreement beyond chance; .40 to .75 for fair to good agreement beyond chance; and below .40 for poor agreement beyond chance (Banerjee *et al.* 1999).

A sample study was conducted to evaluate the usefulness of the classification system. The classification of activities in the valve replacement project was presented as an example to test the usefulness of the classification system. The goal was to analyse the activities throughout TAM execution, classify the activities according to the categories proposed in the classification system, and identify the activities which could be improved or removed from a lean perspective. The six interviewees were asked to measure the VA and NVA in the selected sample using the standardised classification system.

3.4. Research Method for Objective 3

Objective 3 is to develop an innovative Enhanced-VSM framework for a structured application of VSM to turnaround process. Figure 3-3 illustrates the processes of framework development and validation.

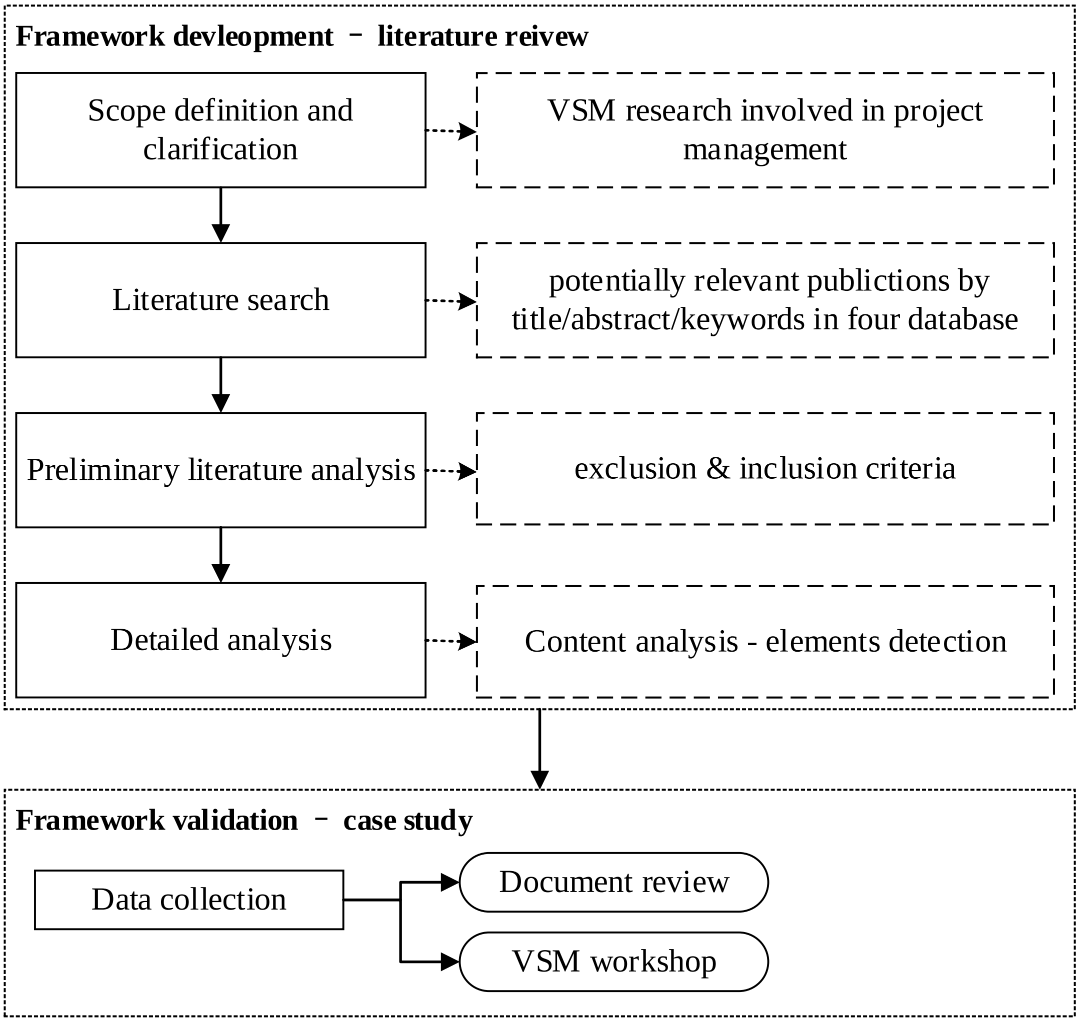

Figure 3-3: The Process of Framework Development and Validation

3.4.1. Enhanced-VSM Framework Development

Literature review

First, a literature review of VSM implementation in TAM projects has been conducted to identify current achievement and highlight the critical issues which need to be solved. A systematic literature review is defined as “a replicable, scientific and transparent process … that aims to minimise bias … by providing an audit trail of the reviewer's decisions, procedures, and conclusions” (Tranfield, Denyer, and Smart 2003). The review followed the four phases (Svejvig and Andersen 2015): (1) scope definition and clarification; (2) literature search; (3) preliminary literature analysis; and (4) detailed analysis.

Phase 1: The scope of this study focused on the applications and research outcomes of VSM application in TAM projects as well as project-based literature. Each TAM project presents a unique work scope and context, and must be examined accordingly—following a unique maintenance process for logic and safety constraints. The coverage of this review included most of the VSM studies in project management.

Phase 2: The search process was conducted in four databases. The keywords of VSM and project management were applied in the area “title/abstract/keywords”. Table 3-7 shows the preliminary search results:

Table 3-7: The Preliminary Search Results

Database	Scopus	ProQuest	ScienceDirect
Search results	119	82	19

Phase 3: The search resulted in a total of 220 (75 of them are repetitive articles) in the three databases by reviewing the title, abstract and the main contents. Some studies were excluded. The exclusion criteria included: (1) VSM application in non-project-based production environment, e.g. service and administrative process, government, and product development, were excluded; (2) VSM application for analysing supply chain in projects were excluded as the productive process is similar to manufacturing; (3) editorials and book reviews were excluded. A total of 26 articles was therefore selected.

Then, a manual review of the 26 articles was conducted to identify papers that were related to VSM. The manual review focused on whether there were: (1) discussion of the comparisons of VSM implementation in process-based production (e.g. manufacturing industry) and project-based production (e.g. construction industry); (2) discussion of the shortcomings/limitations of VSM application in project-based production; (3) discussion of the shortcomings/limitations of VSM application in TAM projects. A total of 5 articles was selected after the manual review.

Phase 4: Detailed content analysis was conducted to summarise the differences, difficulties, and limitations. Table 3-8 shows the results of the analysis.

Table 3-8: The Results of Analysis

Articles	Results of discussion
(Yu *et al.* 2009); and (Yu *et al.* 2011)	Both publications introduced the application of VSM in modular construction projects in Canada. It is found that VSM was applicable in a project environment. These studies discussed the differences between project management and manufacturing process management. The differences are considered as the difficulties that prevent the adoption of the up-adapted VSM in the project context. The difficulties and guiding principles include: 1) the unique construction process compared to a repetitive value stream, which is normally the target of VSM implementation; 2) the massive effort required for data collection and analysis, lean training, team set up; 3) the lack of a full track of construction processes; 4) the challenges of data collection from site investigation and direct observation, due to high variability and complexity in the construction process; 5) the non-applicable of the key concepts/elements used in VSM in the construction context; 6) the complex procedures of value stream selection in the lengthy construction process; 7) the differences in the required level of mapping.
(Shou *et al.* 2017)	The authors highlighted the impact of the features of value streams and the contexts of the flows to the VSM application. The differences of VSM application between project and manufacturing were analysed from the four aspects of VSM application procedures: target process selection, current state analysis, future state improvement, and practical Action Planning. The comparison revealed that: 1) the current performance analysis focuses more on process variability to cope with variations and uncertainties in project

Articles	Results of discussion
	workflow; 2) process improvement focuses on applying work restructure or standardisation to manage workflow variability; 3) the benefits of VSM application are related to the time reduction, and 4) process standardisation is identified as the key factor for efficient VSM application in project context due to the variable feature. It is argued that the reasons leading to the differences are: 1) the non-applicable of the adoption of lean metrics/ techniques in non-manufacturing context; 2) the inconsistent features of the value stream: process-driven vs project-driven; 3) the effort required for data collection; and 4) the inconsistent contexts of the flows.
(Shou *et al.* 2015)	It has been proven that VSM is available in time-sensitive TAM environment. However, some resistances have been identified to the VSM application in maintenance operation: 1) the vague VA and NVA definition is inadequate to be applied in a TAM environment; 2) huge variations in maintenance process, which makes it difficult to map the value stream; 3) lean tools designed for future state map are difficult to be used in a TAM environment.
(Pasqualini and Zawislak 2005)	The authors have discussed the application of VSM in construction projects. Some of the adaptations of VSM application in construction have been suggested :

Articles	Results of discussion
	1) Select a stage of the productive process in construction rather than a family of productions. 2) Collect the data within the whole process to obtain an average production data due to the difficult to observe the data directly at shop floor. 3) Analyse the data based on the stages of construction. It has highlighted the differences of the value streams in manufacturing and construction: multiple orders of a certain product in a period of time in contrast to a single order with a scheduled deadline. 4) Interpret the proposition according to the characteristics of construction when analysing the current process (waste identification). 5) Defining the improvement based on the need of final users (buyers)

Elements Detection

Based on the literature review, the detailed analysis provided supporting elements to the development of Enhanced-VSM framework in TAM projects. The reviewed papers have indicated that the VSM implementation on non-repetitive and complex process, such as the TAM process, is not as straightforward as that on manufacturing. The elements for enhancing current VSM research for the efficient VSM implementation in TAM projects were summarised as:

- Work scope selection

  It is not common to consider the whole TAM system as a single product family because the maintenance work involves different purposes and priorities. It is necessary to identify the desired scope first when applying VSM to a complex production environment (Pasqualini and Zawislak 2005). Furthermore, such workflow is not determined by locations and has a production line (which is very commonly seen in the manufacturing environment). Instead, maintenance staff members move from one activity to another with the assistance of resources, such as equipment, tools, information, and material (Tommelein, Riley, and Howell 1999). In addition, due to the different characteristics between shutdown maintenance operation and manufacturing production, the specific maintenance procedures and techniques in TAM make the traditional data collection by direct observation often not feasible (Shou *et al.* 2015). High risk and complexity of TAM process pose extreme difficulty of setting a group of researchers to work on site. Besides, manufacturing has continuous and routine production. The performance measurement of manufacturing is therefore conducted by using the production data of the ongoing process. On the other hand, the maintenance in TAM is a specific short-term and non-repetitive operation. This feature, makes it impossible to adopt the same method to collect the process data in TAM. Therefore, the elements need to be considered at this phase should focus on:

- ➢ Critical work scope selection
- ➢ Value stream selection
- ➢ Data collection

- Current process measurement

The different practices of value definition and evaluation should not be overlooked. Different to manufacturing, where the production control acts directly on the production processes, project control in TAM focuses on improving stability that is related to the reliability of workflow planning, and efficiency of execution unit (Institute 2000). Meanwhile, lean maintenance centres on waste elimination to improve plant reliability. Therefore, the value in TAM focuses on plant productivity and control efficiency of the operation process. This is distinctly different from the traditional definition of value from the customer’s point of view. Consequently, the measurement of maintenance performance should not be restricted to activities that contribute to the form, fit or function of the material flow, but focus on the investigations of the quality of production execution. Accordingly, the elements of enhancement include:

- ➢ The definition and classification of VA and NVA in TAM workflow
- ➢ Indexes of current process measurement

- Current state analysis

Waste elimination in current state analysis is another important challenge. The massive effort required in removing waste and the huge economic impact of any change make the practitioners hesitated to adopt new methods (Bevilacqua *et al.* 2005). There is one element has to be considered to facilitate efficient VSM application in TAM:

- ➢ Waste (root cause) analysis and prioritisation

- Lean tools application in future state improvement

Because of the differences of value creation and evaluation of TAM and manufacturing, the traditional lean tools developed for reducing waste in the manufacturing process cannot be directly applied in TAM projects (Shou *et al.* 2017). Some researchers have investigated the feasibility of the lean tools to remove waste in the project environment. In manufacturing, continuous flow is used to eliminate stagnation in between the two operations. Nevertheless, the application of this lean tool has a high requirement to the process reliability as any delay of an operation can result in interruption of the entire processes. As mentioned by Yu *et al.* (2009), project is a site-based production, the maintenance execution is impacted by many unavoidable variables such as weather and changes. In addition, the involvement of various trade contractors and massive workers makes it harder to have a uniform and reliable concern of the process efficiency. Therefore, it is not practical to design a continuous flow of project processes due to these variables and variations.

Takt time, supermarket, Kanban, FIFO, and pacemaker are the four lean tools which are proposed to enable customer-driven pull production system in the manufacturing process. However, in construction projects, the client's needs are confirmed at the beginning of the project. In other words, the work scope and duration of the project is confirmed with great certainty. Therefore, the pull-driven takt time needs to be adapted to accommodate the push-driven project management (Yu *et al.* 2009).

According to Frandson, Berghede, and Tommelein (2013) and Frandson, Seppänen, and Tommelein (2015), balanced production rate in project process refers to the desire to create a stable pace of work for each trade crews, with each trade proceeding through a sequence of zones. Supermarket and FIFO lane are both the methods to manage flow fluctuation. However, the project execution processes are composed of thousands of activities and the operation times have huge variations due to the different operation requirement. It is almost impossible to streamline the construction process by following one end-process execution pace. Therefore, the lean tools pacemaker and supermarket are not available to accommodate project-based production rate. The FIFO lane includes both quantity and sequence information and it is practical to use it to improve resource reliability and availability to meet operation requirement by managing the variations and production sequences. It is indicated that the enhancement in the future state should focus on:

- Lean tools selection and application

3.4.2. Enhanced-VSM Framework Validation

Yin (2013) defined the case study research method as *an empirical inquiry that examines contemporary phenomenon within its real-life context, when the boundaries between phenomenon and context are not clearly evident and in which multiple sources of evidence are used.* A case study allows the researchers to gain an in-depth understanding of the phenomenon under investigation. In this regard, a case study is used for exploring new phenomena where quantitative research methodologies are not possible or appropriate (Benbasat *et al.* 1987; Yin 1994). The method of case study is greatly recommended for research where theories are at their formative stage (Eisenhardt 1989, Yin 2013). It is a relevant approach adopted to answer the research questions:

1) How does the framework work in practice?

2) Can the framework improve the maintenance performance?

A brief introduction of the selected case

The Enhanced-VSM theory framework was tested in the turnaround process of a Liquefied Natural Gas (LNG) plant in Karratha, Australia. The selected TAM project is a major shutdown conducted in 2016. The 28 days shutdown involved more than 1000 functional units in two LNG trains. The scope of maintenance work consisted of a gas turbine major overhaul, valve overhaul, internal tray modification, and other shutdowns. The shutdown had cost a A$46.4 million operating loss and a A$37.1 million capital expenditure. The project was planned and carried out using classic project management techniques, Primavera and SAP software. The shutdown was completed 1.5 hours ahead of target duration. However, a cost overrun has been observed due to the huge variations of the actual maintenance process to the planned schedule.

Data collection

It is recommended that evidence and information obtained through a case study be gathered from different sources as a way to triangulate results (Yin 2013). In order to enhance the reliability and validity, data is therefore collected from (1) a comprehensive review of the documents of the selected maintenance project; and (2) VSM development workshop with key participants. The mixed method was adopted to reduce a single source bias. It is argued that much more reliable results can be produced by using the results from multiple methods to complement each other (Fellows and Liu 2015).

According to the principles of critical work scope selection, the purpose of the comprehensive review was to identify the most critical work order that led to risks of project overdue or cost overrun. Therefore, this part mainly included:

- The review of work breakdown structure. The whole TAM project was broken down according to the level of structure. The review was related to how many maintenance WOs and work packages have been developed, what are the functional units in each WO and WP, and how many activities have been conducted within WPs.

- Schedule and cost analysis for each WO. An analysis of designed buffer time, variations of scheduled duration, activities, and resources that were related schedule and budget of each WO were conducted.

- Schedule of the project: tool activities performed by work crews.

- Work package: activities conducted to finish the job in a work package, which include:

    - Quality control: quality management related activities

    - Safety management: safety management activities

    - Site management: site logistic management activities

    - Administrative management: administration activities

    - Delay cards: activities of issue report in progress

The purpose of the VSM workshop was to streamline the maintenance process and provide information which cannot be shown from the documental analysis. In this research, eight experts were invited to: (1) map the current state process of the selected value stream following the rules proposed in Enhanced-VSM framework, (2) verify information about maintenance execution for each process by collecting the operation data for each activity directly from the on-site participants, and (3) investigate the root causes of the waste. Table 3-9 shows the experts' background information. As can be seen, the experts included turnaround general manager, superintendent, schedulers, vendors, and contractors, covering the key staff required for the process planning and control. They were the critical work crews involved in the selected TAM project.

Table 3-9: Profile of Experts

No.	Interviewee	Expertise
1	TAM schedule planner from client	Schedule planning and control
2	TAM schedule planner from client	Schedule planning and control
3	WPs designer from client	WPs design and management
4	WPs designer from client	WPs design and management
5	Production manager from client	Permit system planning and control
6	TAM superintendent from client	Process management
7	Site manager from contractor	Maintenance operation
8	Maintenance vendor	Off-site component maintenance

3.5. Research Method for Objective 4

Objective 4 is to investigate the capability of 4D BIM technique in improving Action Plan development and implementation. Figure 3-4 illustrates the research methods implemented for achieving this objective. The development of the 4D BIM framework started with the reference and literature analysis of previous BIM studies in building and infrastructure industries. Then, a draft 4D BIM framework that could be used in TAM projects was proposed by considering the specific characteristics of TAM projects. Thirdly, TAM experts were asked to examine and finalise the proposed 4D BIM framework. All of the selected experts had been involved in a number of real plant TAM projects in the last five years. Finally, a case study was used to evaluate the effectiveness of the proposed 4D BIM framework in improving Action Plan development and implementation. Each method is discussed in details in the following sections.

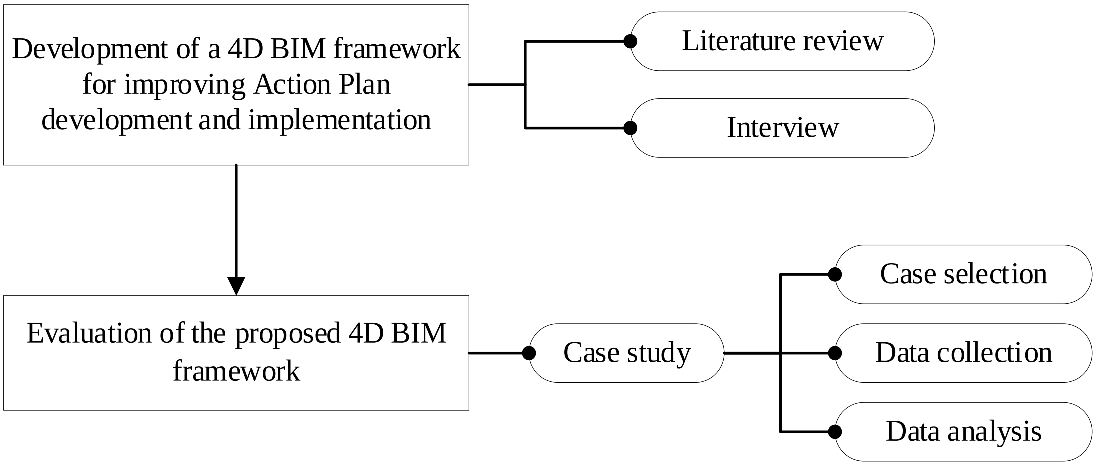

Figure 3-4: Research Method for Developing and Evaluating a 4D BIM Framework

3.5.1. 4D BIM Framework Development

4D BIM technique has been widely applied in building and infrastructure projects, and has proven itself by improving project planning and control. However, limited research has been found in utilising 4D BIM technique in TAM projects. Therefore, there is a need to develop a 4D BIM framework first that complies with the characteristics of TAM projects. According to the literature review in Sections 2.5.2 and 2.5.3, the development of the 4D BIM framework for TAM projects should follow the following two rules.

(1) The level of detail of each 4D BIM simulation should comply with its corresponding TAM planning phase (i.e. milestone planning, work development planning, detailed planning, or site execution planning); and

(2) The level of detail of each BIM model should support the corresponding 4D BIM simulation development;

A draft version of the 4D BIM framework was developed after the literature review which consisted of four different levels of 4D BIM simulation, i.e. Train, Plant, System, and Batch level. Five TAM experts were invited to examine and finalise the draft version. They came from five different divisions and were critical to the success of a TAM project. The first interviewee was a TAM manager who had more than 20 years in planning and managing TAM projects. He suggested to reduce the four levels of 4D BIM simulation to three because most of the TAM projects focused on one train. Therefore the levels of Train and Plant could be combined as one level. The second interviewee was a TAM planner who had more than 5 years in TAM planning by using Primavera 6 (i.e. a scheduling software). She highlighted the importance of the 4D BIM simulation on the Batch level because traditional planning tools such as Primavera 6 could not efficiently handle a large number of concurrent activities that occurred in a congested work space. In addition, she contributed significantly to the level of detail definitions for the 4D BIM simulation. The third interviewee was a TAM work pack developer who had more than 10 years in TAM planning and work pack development. He agreed with the suggestion proposed by the TAM manager (i.e. combine the levels of Train and Plant into one) and contributed to the BIM model level of detail definitions. The forth interviewee was a TAM front-end superintendent who had more than 10 years in TAM planning and control. He also agreed with the suggestion of combining the levels of Train and Plant into one level. However, he highly recommended to add another level, i.e. 4D BIM simulation on the Activity level, which took account of detailed operations and maintenance work crews including their working locations and travelling paths. The fifth interviewee was a TAM permit manager who had more than 15 years in plant operation and maintenance. He agreed with the suggestions proposed by the TAM manager and front-end superintendent, respectively. In addition, he highlighted that a significant number of construction delays were caused by inefficient permit management. Therefore, it was necessary to consider the permit management through the four levels of 4D BIM simulation. After the interview, the draft 4D BIM framework for TAM projects was revised according to their comments. Detailed explanation of the final framework can be found at Section 7.2, Chapter 7.

3.5.2. 4D BIM Framework Evaluation

Case study method have been widely used in construction industry to evaluate new approaches or techniques. A case study is an objective, in-depth examination of a contemporary phenomenon where the investigator has little control over events. In this thesis, a real TAM case was selected to evaluate the effectiveness of the proposed 4D BIM framework in improving Action Plan development and implementation. Detailed case information including data collection and analysis is described as follows.

(1) Case selection. There are three types of TAM projects in terms of their scale: small (i.e. around ten days), medium (i.e. 2-3 weeks), and major (i.e. 3-5 weeks). A major TAM project always contains more activities, teams, and resources. Planning, coordination, and communication in a major turnaround are more challenging than those in a small/medium one. Therefore, a major plant turnaround project conducted by Woodside Energy Limited in 2015 was selected as the case study. This turnaround project consists of LNG Train 5 and Fractionation Train 1 unit outages. The key activities involved in this turnaround include: (1) Turbine major inspection; (2) Statutory vessel inspections; (3) Compressor blade carrier change-out; (4) Bearing and seal inspections; (5) Tray modifications; (6) Molecular sieve bed change-out; (7) Mercury guard bed change-out; and (8) Valve overhauls, upgrades and replacements.

The full scope of work was reviewed and assessed with a criticality assessment and finally the scope agreed. All scope items that require this Turnaround to execute the work was frozen. The outage was managed by the Turnaround Team. In terms of magnitude the total Turnaround peak work force was approximately 1,500 personnel across both shifts. The Turnaround commenced on 3th September 2015 for an expect duration of 33 days. The initial budget for this turnaround project was 64.1 million dollars. The target turnaround duration was 28 days and the expect duration was 33 days.

(2) Data collection. The collected data includes: a focus group study; documents; informal meetings and discussions; observations; and feedback on reports. The focus group study was conducted after the turnaround with representatives from each different teams. A total of 17 participants were selected which consists of: two from engineering team, three from turnaround management team, four from site execution team, two from operation team, one from rigging and lifting team, two from human logistics team, two from commissioning team, and one from health and safety team. The main focus of the focus group study is to:

- List all the improvement achieved in this turnaround project and classify them into categories;
- Determine the drivers of each identified improvement, questions such as “For each improvement, is the 4D BIM the main driver?”, “If no, what is the main driver of this improvement?” were asked;
- Discuss the contribution of the improvement strategies proposed in the Future State (i.e. Standardisation, Dynamic pull flow, and Location-based levelling). Participants were also allowed freedom to discuss their experiences and thoughts about the 4D BIM implementation in their teams.

Cost information were collected and updated daily to provide management with accurate cost status information to facilitate effective cost control. The progress to schedule and associated S-curve were updated daily during the Execution phase. Planning and progress of all the Turnaround phases is tracked through the use of the campaign checklist. The Tracking of progress during Pre-Execution activities is via the Pre-Turnaround weekly report. Tracking of progress of the work order resourcing, work pack preparation, permit preparation, purchase order issue and preparation of plan are tracked in Turnaround Planning Sheet. Tracking of progress through the Execution phase is by the Turnaround Daily Execution Report.

(3) Data analysis. In order to measure the effectiveness of the Action Plan developed through the proposed 4D BIM framework, a previous TAM project with the same working scope was selected as a benchmark. The following three types of analysis were conducted:

- Analysis of Value-adding and Non-Value-adding Activities. Five VSM metrics (i.e. Total amount of cycle time, Total amount of processing time, The average percentage of on time start, VA ratio, and The number of interfaces) were chosen to calculate the "Transformation rate" which indicated how many percentage of the future state had been achieved by using 4D BIM technique. The greater the "Transformation rate" is, the more effective the Action Plan is.

- Analysis of time and cost reduction. Four time-related indicators were measured and compared to analyse the time reduction, i.e. "Actual Duration of the Previous TAM project", "Initial Expected Duration of the Current TAM Project", "Target Duration of the Current TAM Project", and "Actual Duration of the Current TAM Project". Three cost-related indicators (i.e. Initial Budget, Budget after optimisation, and Actual Cost) were calculated and compared to analyse the cost savings.

Analysis of the Contribution to the time and cost reduction. It is unreasonable to attribute all the successful outcomes to the 4D BIM implementation. Other factors such as lessons learned from previous TAM projects also made a significant contribution to the project achievements. In order to understand the contribution of each factor, the TAM team conducted an internal focus group study after the turnaround. A total of 17 representatives attended the focus group session (as shown in Table 3-10). The main focus of the focus group study was to: (1) list all the improvement achieved in this turnaround project and classify them into categories; (2) determine the drivers of each identified improvement, questions such as "For each improvement, is the 4D BIM the main driver?", "If no, what is the main driver of this improvement?" were asked; (3) discuss the contribution of the improvement strategies proposed in the Future State (i.e. Standardisation, Dynamic pull flow, and Location-based levelling). Participants were also allowed freedom to discuss their experiences and thoughts about the 4D BIM implementation in their teams. Detailed results of the focus group study is summarised and explained in Section 7.4, Chapter 7.

Table 3-10: Profile of the 17 Representatives

No.	Role	Team
1	General Manager for Maintenance	Maintenance Team
2	Operation Manager	Operation Team
3	TAM Manager	TAM Team
4	TAM Planner 1	TAM Team
5	TAM Planner 3	TAM Team
6	TAM Work Pack Developer 1	TAM Team
7	TAM Work Pack Developer 2	TAM Team
8	TAM Front-End Superintendent	TAM Team
9	Permit Manager	Operation Team
10	Safety Manager	HSE Team
11	Quality Manager	Quality Team
12	Site Manager	Site Supervision Team
13	Mechanical Discipline Leader	Mechanical Team
14	Inlec Discipline Leader	Inlec Team
15	Valve Discipline Leader	Valve Team
16	Rotating Manager	Rotating Team
17	Engineering Manager	Engineering Team

3.6. Summary

This chapter presented the discussion of research philosophy, method selection, and data collection and analysis for each objective in this research. The methodology adopted in this research include literature review, focus group study, and case study. A review of the literature from the VSM application in manufacturing, healthcare, construction, service and product development sectors attempts to identify the differences and key factors of efficient VSM implementation (research objective 1). The current application of VSM in five sectors was useful to provide appropriate direction of VSM research.

Focus group study and structured interview were adopted to evaluate and validate the proposed standardised VA and NVA system (objective 2). 6 experts with expertise on TAM projects were targeted. The initiated standardised framework were evaluated and improved through the processes. These two methods were also adopted to validate data collected in the selected case study (objective 3)

Case study were conducted to examine the effectiveness of the proposed classification system in practice (research objective 2) and to validate the enhanced-VSM framework (research objective 3). The capability of 4D BIM technique in improving Action Plan development and implementation were investigate from the case study as well (research objective 4).

Chapter 4: VSM Application in Cross Sectors

4.1. Introduction

This chapter aims to review the-state-of-the-art development of VSM in five sectors, including manufacturing, healthcare, construction, product development, and service sectors. So far, there has little scientific research of the differences of VSM application in different production environment. Therefore, this chapter provides detail evidence of issues related to the use of VSM in TAM environment which may require immediate attention. A total of 131 journal articles are reviewed and analysed from the period of 1999 to 12/2016. The analysis covers the complete implementation cycle of VSM, including metrics for current state map, improvement techniques for future state map, benefits and achievements of VSM application, and critical success factors for VSM implementation. Cross-sector comparisons and investigations are conducted to understand the differences of VSM implementations in various sectors to facilitate VSM development and increase the number of successful VSM implementation (Figure 4-1). The results suggest that understanding value and waste in a diverse value stream environment and ensuring the suitability and usability of traditional lean metrics/techniques within the different flow settings are central to the VSM development.

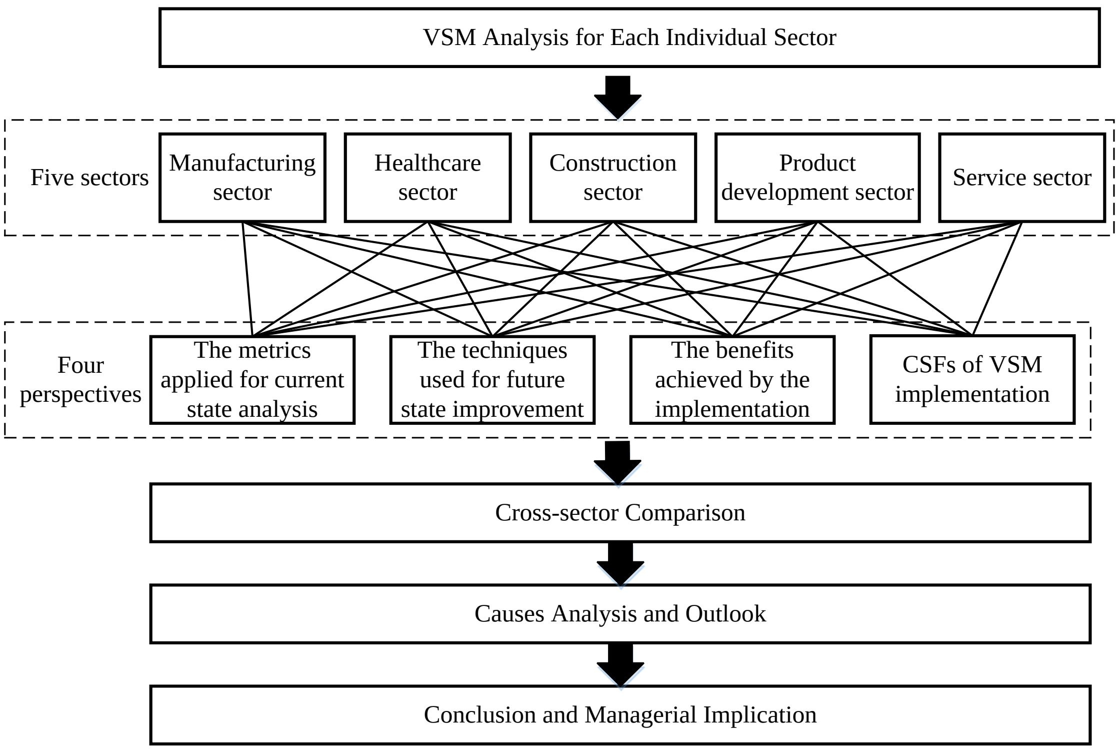

Figure 4-1: The Framework of Cross-Sector Review

4.2. Overview of Selected VSM Publication

Preliminary analyses were conducted to analyse the basic descriptive information of each selected paper, including publication year, the distribution of journals, and the distribution of articles by research topics and sectors.

4.2.1. Distribution by Year of Publication

Figure 4-2 shows the annual number of publications during the period from 1999 to 12/2016, which shows that VSM has attracted much attention since 2008 and it has reached its peak in 2014.

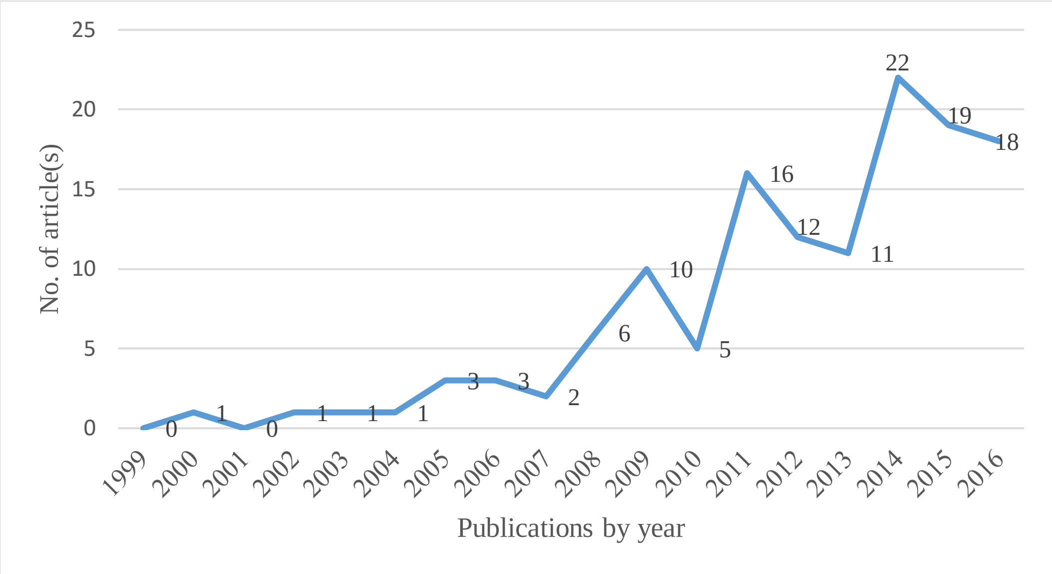

Figure 4-2: Distribution of VSM Articles by Years (1999-12/2016)

4.2.2. Distribution of Articles by Journal

Figure 4-3 presents the distribution of selected publications by journals. There are 59 journals which include VSM-related publications. Among these leading journals, International Journal of Production Research and International Journal of Advanced Manufacturing Technology have by far published the largest number of articles (18 and 17 articles, respectively).

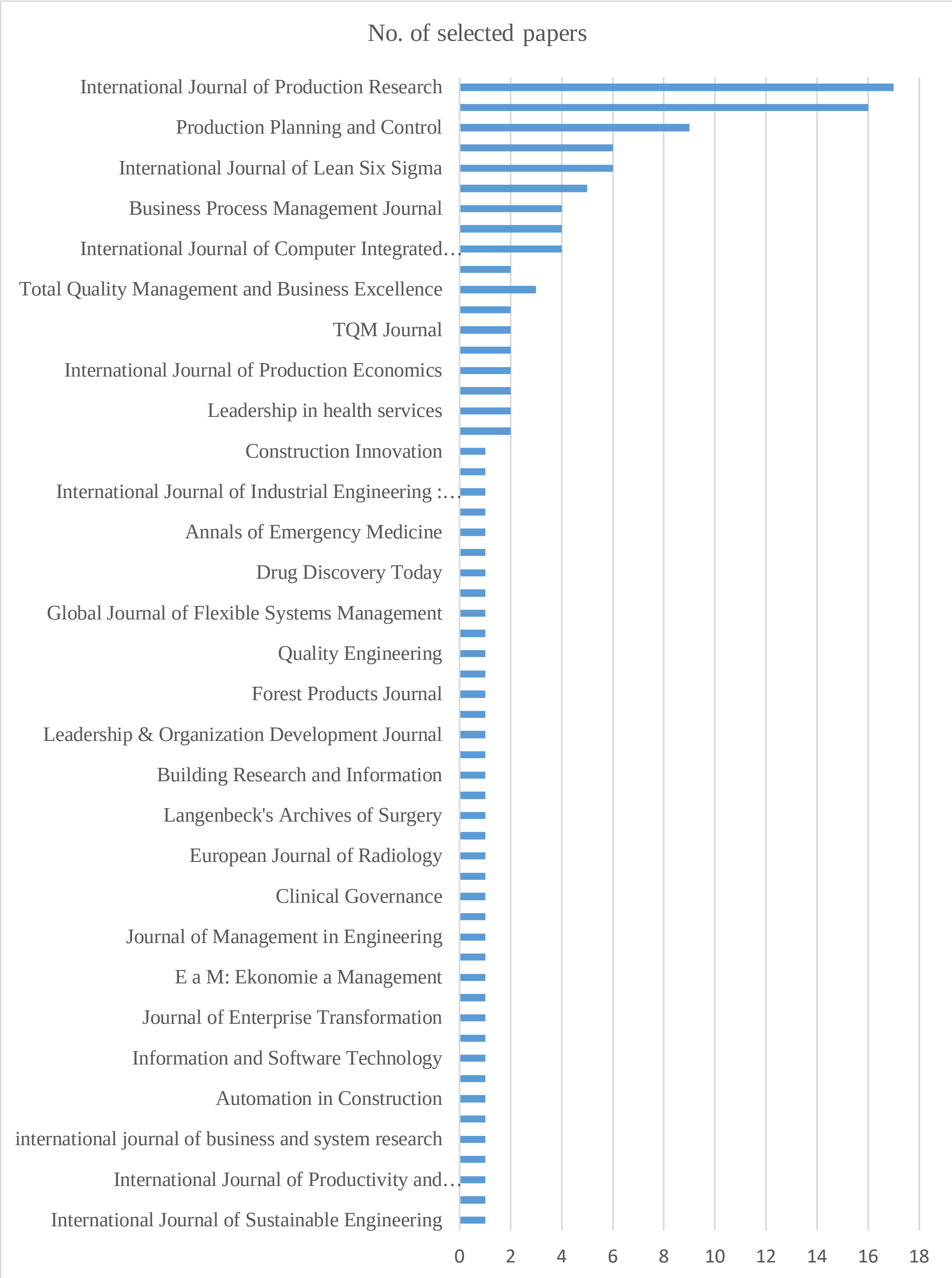

Figure 4-3: Distribution of VSM Articles by Journals

4.2.3. Distribution of Articles by Sectors

The content study reveals that VSM research is mostly related to five major sectors, namely, (1) manufacturing, (2) healthcare, (3) construction, (4) production development, and (5) service. It should be noted that some articles cover more than one sectors. For example, Doğan and Unutulmaz (2014) discussed the use of VSM for reaching management actions in the healthcare environment. Such management actions can be categorised as service because the service sector involves a wide range of business activities which produces and trades intangible goods such as data, information, and knowledge (Miozzo and Soete 2001). However, it is listed in the healthcare sector as such management actions may be influenced by the characteristics of healthcare.

Table 4-1 presents the distribution of publications by sectors. It indicates that great research efforts have been made in the manufacturing sector. It is notable that the research on healthcare sector has been rising rapidly since 2009.

Table 4-1: The Distribution of Publications by Sectors

	Period (Year)					
Research Sector	1999-2003	2004-2008	2009-2013	2014-2016	Subtotal	Percentage
Manufacturing	2	11	37	41	91	69%
Healthcare	0	3	9	7	19	15%
Construction	1	0	4	5	10	8%
Production Development	0	1	1	6	8	6%
Service	0	1	2	0	3	2%
Subtotal	3	16	53	59	131	100%

4.3. VSM Implementation in Manufacturing Industry

Manufacturing is the sector which had the largest proportion of VSM implementation. Within the 91 publications, 2 out of them are literature review (see (Singh, Garg, and Sharma 2011) and (Dal Forno *et al.* 2014)) in terms of VSM implementation in the manufacturing sector. The automobile is the main industry to use the VSM as part of its process performance measurement and improvement program. VSM has later been successfully applied in other manufacturing industries such as electronics manufacturing (Li, Cao, and Pan 2012), fishing net production (Yang *et al.* 2015), glass industry (Atieh *et al.* 2016), textile industry (Hodge *et al.* 2011), wine industry (Jiménez *et al.* 2012), and food production industry (Tanco *et al.* 2013; De Steur *et al.* 2016), etc. Various applications have been developed in this sector, such as basic VSM implementation for reducing cycle time (Seth and Gupta 2005), reducing waste in supply chain (Jain *et al.* 2008; De Steur *et al.* 2016), increasing productivity and reducing lead time in assembly and production-logistic processes (Kuhlang, Edtmayr, and Sihn 2011), improving leadership in organisations (Emiliani and Stec 2004), and even enhancing system and method competencies of individuals and organisations (Sunk *et al.* 2016). Furthermore, enhanced VSM application to address shortcomings of VSM within different manufacturing environment have been suggested. For example, Braglia, Carmignani, and Zammori (2006) proposed a new VSM for complex production systems, McDonald, Van Aken, and Rentes (2002), Abdulmalek and Rajgopal (2007), and Atieh *et al.* (2016) etc. introduced simulations to have the dynamic value stream process review. Besides, the research on using VSM to capture sustainability performance have emerged and became an important research direction in this domain (Faulkner and Badurdeen 2014; Brown, Amundson, and Badurdeen 2014).

4.3.1. The Metrics for Current State Analysis

Table 4-2 shows the metrics have been employed in the manufacturing sector. The measurements are typically related to the general production process – e.g., production cycle time, lead time and inventory, which have the largest number of application (69%, 67%, and 58% respectively).

Table 4-2: The Metrics for Current State Analysis in the Manufacturing Sector

Types of Process	Metrics	No.	Percentage
Production efficiency	Cycle time	61	69%
	Lead time	59	67%
	Inventory	51	58%
	Value-added ratio	36	41%
	Manpower	32	36%
	Changeover time	25	28%
	Uptime	24	27%
	Processing time	25	28%
	Shift	13	15%
	Setup time	13	15%
	Idle time	8	9%
	Batch	9	10%
	Waiting time	6	7%
	Transportation	9	10%
	Available time	5	6%

Types of Process		Metrics	No.	Percentage
		Yield	2	2%
		On time delivery	1	1%
		Rework	1	1%
		Defect	4	5%
Machine performance		Mean time between failures	2	2%
		Mean time to repair	2	2%
		Machine reliable	1	1%
Sustainability	Economy	Value added cost	3	3%
		Non-value added cost	3	3%
		Raw material consumption	3	3%
		Power consumption	2	2%
		Total energy consumption	3	3%
		Oil and cool consumption	1	1%
		Material utilisation rate	1	1%
	Environmental	Carbon footprint	3	3%
		Water eutrophication	2	2%
		Air acidification	1	1%
		Water consumption	4	5%
	Society	Physical load index	3	3%
		Work environment risks	3	3%
		Noise level	3	3%

4.3.2. The Techniques for Future State Improvement

The 27 techniques for eliminating waste in FSM within the manufacturing sector have been classified into three categories: lean techniques, IT-support techniques, and management related techniques (Table 4-3). In lean techniques, takt time (44%), Kanban pull system (30%), and 5S (19%), continuous flow (17%), and kaizen (17%) are the most popular techniques have been employed.

IT-support techniques are mostly related to the use of information technology (IT), such as RFID (Tabanli and Ertay 2013) and Virtual Reality (Tyagi and Vadrevu 2015) to support waste identification and elimination in a dynamic environment. Management related techniques are related to management support, such as early involvement and training, which may be needed for a successful implementation of VSM.

Table 4-3: The Techniques for Future State Improvement in Manufacturing Sector

Types of process	Techniques	No.	Percentage
Lean techniques	TAKT time	39	44%
	Pull system (Kanban)	26	30%
	5S	17	19%
	Continuous flow	15	17%
	Kaizen	15	17%
	Supermarket	13	15%
	Production levelling	13	15%
	Work standardisation	10	11%
	Pacemaker process	9	10%
	Constant work in progress reduction	9	10%
	Single piece flow	8	9%
	FIFO	9	10%
	Continuous improvement	7	8%
	Heijunka box	6	7%
	Cellular manufacturing	4	5%
	SMED	5	6%
	Total productive maintenance	5	5%
	Just in time	1	1%
	Poka yoke	1	1%
Technology-related techniques	Information technology	5	6%
	visual aid	2	2%
Management-related techniques	training	11	13%
	Early involvement	10	12%
	Involvement of stakeholders	6	7%
	Change management	1	1%
	Risk evaluation	1	1%
	Stage inspection	1	1%

4.3.3. The benefits for VSM Implementation

40 different types of benefits have been obtained from VSM implementations in the manufacturing sector. Table 4-4 shows the top 15 benefits which have been obtained in more than 2 publications. The improvements on inventory, lead time, cycle time, and manpower are the top four benefits recognised by researchers, with average achievements 70.23%, 56.17%,

52.58%, and 37.39%, respectively).

Table 4-4: The Benefits for VSM Implementation in Manufacturing Sector

Improvement index	Inventory	Lead time	Cycle time	Manpower	Value-adding time	Defect	Non-value adding time
No. of articles	24	17	9	8	4	4	3
Average improvement	70.23%	56.17%	52.58%	37.39%	41.83%	13.25%	64.23%

Improvement index	Floor space	Process ratio	Uptime	Productivity	Travel distance	Production time	Raw material consumption
No. of articles	3	3	2	2	2	2	2
Average	35.48%	45.54%	2.36%	31.93%	57.78%	23.34%	19.00%

4.3.4. The CSFs for Effective VSM Implementation

As can be seen from Table 4-5, 12 CSFs have been identified that allow for effective VSM implementation. Theory refinement and integration is the most commonly identified CSF. The empowered inter-principle lean team, top management support and training and education at the second tier CSFs in this domain.

Table 4-5 CSFs in the Manufacturing Sector

	CSFs of VSM										
Articles	Empowered inter-principle lean team	Top management support	Training and education	Theory refinement and integration	Organisation culture	Communication	IT support	Resources availability	Stage control	Manageable size	Skills and abilities	Strategies alignment
(Abdulmalek and Rajgopal 2007)				*								
(McDonald *et al*. 2002)				*								
(Seth* and Gupta 2005)		*				*						*
(Serrano *et al*. 2008)	*	*	*	*			*		*	*	*	
(Lian and Van Landeghem 2007)				*								
(Chen *et al*. 2010)				*								
(Serrano Lasa *et al*. 2008)				*			*					

Articles	CSFs of VSM											
	Empowered inter-principle lean team	Top management support	Training and education	Theory refinement and integration	Organisation culture	Communication	IT support	Resources availability	Stage control	Manageable size	Skills and abilities	Strategies alignment
(Singh *et al.* 2011)	*		*	*								
(Gurumurthy and Kodali 2011)				*								
(Serrano Lasa *et al.* 2009)			*	*								
(Lu *et al.* 2011)				*								
(Bertolini *et al.* 2013)				*								
(Saad *et al.* 2006)	*	*			*			*			*	
(Dal Forno *et al.* 2014)	*	*	*		*	*			*	*	*	*

4.4. VSM Implementation in Healthcare Sector

In recent years, organisations in the healthcare sector are pressured to reduce patient treatment time and improve management efficiency to remain competitive. Lean thinking has been used for healthcare since 2002 (Brandao de Souza 2009). VSM is one of the most commonly used lean tools for lean implementation in this sector, predominantly in two workflows: administrative process and patient treatment process. The administrative process is related to the delivery of information or materials, procurement, inventory management, etc. Patient flow is related to improving the efficiency of the patient pathway within a hospital/clinic. The reported applications, benefits, and CSFs are composed and presented in Table 4-6.

Table 4-6: Analysis Results of VSM Implementation in the Healthcare Sector

Types of process	Metrics have been applied	Techniques for improvement	Benefits	CSFs
Administrative process	Cycle time (5, 71%) Processing time (3, 43%) Lead time (3, 43%) Inventory (2, 29%) Manpower (2, 29%) Batch size (1, 14%) Availability (1, 14%) Changeover time (1, 14%) Uptime (1, 14%)	Takt time (2, 29%) Pitch production (2, 29%) Continuous flow (2, 29%) FIFO (2, 29%) Pull supermarket theory (1, 14%) Kanban (1, 14%) Cell layout (1, 14%) Standardisation (1, 14%) Managerial strategies (1, 14%)	Reduced customer complaints, 35% Reduced employees overtime, 41% Reduced processing time of Critical business process from 2 days to 1 day Reduced accessioning errors from 7.6% to 5.9% Reduced cost of poor quality about 3 to 9% of the pharmacy's operational budget A reduction of interface problems	Regular and clear communication Leadership Involvement of cross-functional team Availability of data Project selection Training

Types of process	Metrics have been applied	Techniques for improvement	Benefits	CSFs
Patient treatment process	Waiting time (8, 67%) Lead time (6, 58%) Processing time (5, 42%) Cycle time (3, 25%) Value added time (3, 25%) Non-value added time (2, 17%) Length of stay (2, 17%) Manpower (2, 17%) Travel time (1,8%) Transfer time (1, 8%)	Managerial strategies (8, 73%) Standardisation (3, 25%) Takt time (2, 17%) Continuous flow (1, 8%) Cellular layout (1, 8%) FIFO (1, 8%) Pull system (1, 8%) Levelling of patient (1, 8%) Kanban (1, 8%) Kaizen event (1, 8%) 5S (1, 8%) One-piece-flow (1, 8%)	Reduced non-value added time in critical treatment processes, 38% Reduced length of stay, 33% Reduced treatment time, 70% Reduced transitions and travel time of patient, 24%, 44% respectively Reduced waiting time, 75% Improved service level, 61% Reduced human powers, 34% Improved critical business efficiency, 30%	All employees involvement (4) Cross-training Partnerships with colleagues Top management support Manageable size project selection Lean tools identification and modification

4.4.1. The Metrics for Current State Analysis

As can be seen from Table 4-6, the cycle time is the most frequently adopted measurement in administrative process (71 percent), while waiting time is the leading metric in the patient treatment process (67 percent). Table 6 also reveals that the metrics adopted in the healthcare sector are time-related, such as lead time and processing time. The key metric of inventory has been missed in patient-relative process measurement.

4.4.2. The Techniques for Future State Improvement

One interesting finding in the healthcare sector is that the lean techniques developed to solve the classic seven types of waste are not popular in both administrative process and patient treatment process. Only one article (Tortorella *et al.* 2016) follows the FSM guidelines, applying lean techniques such as takt time, continuous flow, FIFO, supermarket, schedule levelling, pitch production, and kaizen in a healthcare organisation. The most commonly adopted approach is managerial strategies to improve process efficiency in the patient treatment process.

4.4.3. The benefits of VSM Implementation

The main benefits of VSM applications in healthcare include reduced employees' overtime (41%) and customer complaints (35%) in administrative processes, and reduced waiting time (75%) and treatment time (70%) in patient flows. There are great improvements in service level based on a quantitative analysis. Although there are clearly many differences of the benefits achieved, commonalities among these benefits are shortened the non-value added time in critical treatment processes and improved service process efficiency.

4.4.4. The CSFs for Effective VSM Implementation

A number of CSFs are identified as important for VSM implementation in the healthcare sector. For example, Bhat, Gijo, and Jnanesh (2016) argued that regular and clear communication, leadership, the involvement of cross-functional team, data availability, project selection, and training are important. Henrique *et al.* (2016) found that all employee involvement and cross-training are important. It is interesting to see the two factors, training and project selection are highlighted in both types of processes. Data availability is mentioned as one of the important factors in administrative processes. In the patient process, employees involvement is rated high. In addition, identification and modification of traditional lean tools to fit in the healthcare process are recognised as one of the key factors.

4.5. VSM Implementation in Construction Industry

The construction sector has made significant progress in developing project management theory since the concept of Transfer-Flow-Value (TFV) from lean theory was introduced (Koskela 1992). Under this research on lean construction, the fundamental assumption is that lean manufacturing principles can be applied to construction processes, and will lead to improvements in construction process effectiveness. Moreover, lean practices have been widely applied to measuring and monitoring carbon efficiency (Wu and Feng 2012; Wu, Pienaar, and O'Brien 2013; Wu, Low, and Jin 2013). The construction sector has recognised the functionalities of VSM, and used it as an effective lean tool to improve process performance (Pasqualini and Zawislak 2005). VSM has been recognised as one of the most common lean tools/techniques for enabling sustainability (Ogunbiyi, Goulding, and Oladapo 2014).

Table 4-7 shows the review results of VSM implementation in the construction sector. As can be seen from Table 7, VSM applications in the construction are related to: (1) building component manufacturing; (2) supply chain; (3) administrative management; (4) drawing design; and (5) construction process.

Table 4-7: Analysis Results of VSM Implementation in the Construction Sector

Types of work process	Metrics have been applied	Techniques for improvement	Benefits	CSFs
Building component manufacturing process Supply chain Administrative management Drawing design	Lead time (5, 83%) Processing time (4, 67%) Cycle time (2, 33%) Inventory (2, 33%) Queue or wait time (2, 33%) Uptime (1, 17%) Completion rate (1, 17%) Defects (1, 17%) Manpower (1, 17%) Setup time (1, 17%) Move time (1, 17%)	Pull system (2, 33%) 5S (2, 33%) Standardisation (2, 33%) Kaizen event (2, 33%) Workload-levelling (1, 17%) Restructuring work (1, 17%) In-station quality (1, 17%) Takt time (1, 17%) Batch size minimisation (1, 17%) Theory of constraints (1, 17%) Poka-yoke (1, 17%) Just in time (1, 17%) Visual controls (1, 17%) Early involvement of suppliers (1, 17%) Foster communication (1, 17%) Failure mode and effects analysis (1, 17%) BIM support (1, 17%)	Lead time reduction, 34%; cost reduction, 16% Labour hours improvement Lead time reduction, 25%; total duration reduction of each task, 50% Lead time reduction, 40%; process time Reduction, 25.3%; number of activities reduction, 37.5% Processing time improvement, 36%; total time improvement, 38%	Training and education (2, 33%) Communication and collaboration (1, 17%) Standardisation of precast elements and Precast processes (1, 17%)

Types of work process	Metrics have been applied	Techniques for improvement	Benefits	CSFs
Construction process	Cycle time (2, 67%) Inventory (2, 67%) Contributory work index (1, 33%) Uptime percentage (1, 33%) Performance (1, 33%) Setup time percentage (1, 33%) Metal waste (1, 33%) Lead time (1, 33%) Booking time (1, 33%) Percent started on schedule (1, 33%) Changeover time (1, 33%) Uptime (1, 33%) Yield (1, 33%)	Work restructuring (3, 100%) Work standardisation (3, 100%) Total quality management (2, 67%) FIFO lane (2, 67%) Takt time (2, 67%) waste management (1, 33%) Kanban (1, 33%) Production levelling (1, 33%) Kaizen event (1, 33%) Long-term partnership with trade constrictors (1, 33%)	The standard deviations of total duration and lead times had decreased dramatically.	Standardisation (3, 100%) Training and education (3, 100%) Lean theory refinement (2, 67%) Empowered inter-principle lean team (2, 67%)

4.5.1. The Metrics for Current State Analysis

Lead time (80%) and processing time (67%) are the most commonly adopted metrics to document workflow of the processes. Three articles adapted VSM theory for fundamental construction processes improvement, including reducing the variability of the process (Yu *et al.* 2011; Yu *et al.* 2009) and improving the environmental and production performance (Rosenbaum, Toledo, and González 2013). Cycle time (67%) and inventory (67%) are the two metrics have been used twice. A few new metrics such as percent started on schedule, booking time, contributory work index, and metal waste are designed to represent process stability and environmental performance.

4.5.2. The Techniques for Future State Improvement

Regarding the techniques applied for eliminating waste and improving performance, pull system, standardisation, and kaizen are commonly selected. However, there are relatively few studies focusing on adapting and applying lean techniques to improve processes efficiency. In construction process management, work restructuring (100%), work standardisation (100%), total quality management (67%), FIFO lane (67%), and takt time (67%) are the four tools mainly used for improving construction process.

4.5.3. The benefits for VSM Implementation

It is observed that VSM is an effective tool for improving the productivity of lead time and processing time. However, because of the complexity of project processes, the detailed discussion in terms of the results of the VSM implementation for construction process improvement is not identified.

4.5.4. The CSFs for Effective VSM Implementation

In terms of the CSFs for successful VSM application in construction, training and education are an import factor for VSM adaptation. In the construction process, work standardisation and staff training that is in line with the characteristics of construction is necessary for effective VSM implementation in the future. Lean theory refinement has also been identified as important to assist lean adaption in a construction project.

4.6. VSM Implementation in Product Development Sector

The terminology of "lean product development" emerged alongside the development of lean thinking in engineering. There are 8 lean product development articles focusing on adopting and applying specific VSM to product development process. Table 4-8 shows the review results of VSM implementation in this sector. Research works in this sector use VSM as functional models to describe and evaluate the performance of a product development process. From the process perspective, the primary output of most product processes, unlike manufacturing processes, is information (León and Farris 2011). Consequently, the value in product development processes appears to be found in the flow of information and knowledge, which is transferred in the form of deliverable among the participants (León and Farris 2011). According to McManus (2005), information is valuable if it is useful. That is, valuable information reduces the risk of producing an unsatisfactory product as well as improve the efficiency of development processes (León and Farris 2011). Table 4-8 shows the review details.

Table 4-8: Analysis Results of VSM Implementation in the Production Development Sector

Types of process	Metrics have been applied	Techniques for improvement	Benefits	CSFs
Product development	People involved (4, 50%) Processing time (3, 38%) Cycle time (3, 38%) Waiting time (2, 25%) Value added time (1, 13%) Design cost (1, 13%) Development man hours (1, 13%) Iteration (1, 13%)	Earlier involvement of suppliers (5, 63%) Improved communication to foster Proper information (5, 63%) Pull (2, 25%) Standardisation (1, 13%) Takt time (1, 13%) Continuous flow (1, 13%)	Value added step increment, 30% The percentage of valued added time increasing, 50% Waiting time reduction, 89% The total number of iterations reduction, 53% The cost of component reduction, 5% Development and validation cost reduction, 15% Lead time reduction, 66% Cycle time reduction, 23% Man-hour reduction, 20%	The redefinition of critical lean concepts Communication

4.6.1. The Metrics for Current State Analysis

The review reveals that the research on current state analysis focuses on identifying productive times in process structure and eliminating the inefficient feedback and iterations during knowledge transformation. Therefore, people involved (50%), lead time (38%), and processing time (38%) are the common metrics adopted to track the creation of output value.

The cost of the process has been used as the metric to measure the value-adding activities performance in Tuli and Shankar (2015). However, iteration, which should be applied to measure the efficiency of information processing, has only been employed once (Khurum, Petersen, and Gorschek 2014).

4.6.2. The Techniques for Future State Improvement

The most commonly adopted technique in the product development studied is the managerial solutions, including earlier involvement of suppliers (63%) and improved communication upfront to foster proper information exchange (63%). Lean techniques, including pull (25%), standardisation (13%), takt time (13%) and continuous flow (13%) have been employed in the review articles.

4.6.3. The Benefits of VSM Implementation

Tyagi *et al.* (2015) have achieved increased value-added time, waiting time reduction, and iteration reduction in a product development process. Tuli and Shankar (2015) highlighted the improvement in reducing development cost, man-hours, cycle time and the cost of the component by applying VSM in the design process.

4.6.4. The CSFs for Effective VSM Implementation

Two key factors that contribute to the effectiveness of VSM in product development are identified. Similar to VSM implementation in other sectors, the redefinition of critical lean concepts has been mentioned for promoting the successful VSM implementation (Tyagi *et al.* 2015). Communication is another factor indicated in research (Ali, Petersen, and de França 2015).

4.7. VSM Implementation in Service Industry

In the service sector, work activities have been influenced by relationships, decisions, negotiations, and conflict (Barber and Tietje 2008). Value is co-created by both customers and suppliers through intangible relationships. VSM application in the service sector lies in eliminating delay, errors, inappropriate procedures and improving customer satisfaction. There are three articles discussing VSM implementation in service practice to reveal tangible, and actionable modifications to the sales process (Barber and Tietje 2008), to reorganise the work placement service in a third sector organisation (Paciarotti, Ciatteo, and Giacchetta 2011), and to reveal the non-value-adding activities in the business process (Ray and John 2011). Table 4-9 shows the review results of VSM implementation in this sector.

Table 4-9: Analysis Results of VSM Implementation in the Service Sector

Types of process	Metrics have been applied	Techniques for improvement	Benefits	CSFs
Service process	Lead time (1, 33%) Value adding ratio (1, 33%) Manpower (1, 33%) Cycle time (2, 66%) Waiting time (3, 100%) Inventory (1, 33%) Transportation (1, 33%) Delay (1, 33%) Total number of daily work (1, 33%) Requests (1, 33%) Level of user satisfaction (1, 33%)	Pull system (1, 33%) Standardisation (1, 33%) Collaborative work (1, 33%) Proactively plan for customer needs (1, 33%) Information transparency (1, 33%) Process restructure (1, 33%)	20% value added ratio improvement Work efficiency improvement	N/A

4.7.1. The Metrics for Current State Analysis

Although there is evidence of VSM being used in the service, there is not enough data presented in the reviewed literature regarding its implementation. The current state measurement involves both process performance and the resource involved (Paciarotti, Ciatteo, and Giacchetta 2011). Cycle time and waiting time are the two metrics have been employed by more than two articles.

4.7.2. The Techniques for Future State Improvement

Pull system and standardisation are the two techniques adopted. Managerial improvement strategies of collaboration, proactive plan, information transparency, and process restructure are the main focus in this sector.

4.7.3. The Benefits of VSM Implementation

In the selected three articles, VSM helps achieve increased value-added ratio and improved work efficiency.

4.7.4. The CSFs for Effective VSM Implementation

No article in this sector has investigated CSFs for successful VSM implementation.

4.8. Cross-Sector Comparison Study

The review reveals that VSM has been predominantly adopted in the manufacturing sector. In order to facilitate and increase the number of implementation of VSM in other sectors, cross-sector comparisons are needed.

4.8.1. Comparison of the Metrics Used for Current State Analysis

In general, the VSM application relies on the assumption that desired production processes will be improved by measuring the right metrics. Lead time, cycle time, processing time, inventory and manpower have been used as basic performance metrics in all five sectors. On the other hand, some metrics such as defect and rework are rarely used. This finding suggests that waste identifications in all five sectors focused on excess inventory and lead times. There are some sector-specific metrics based on the review.

- The manufacturing sector has the largest amount of metric categories used for analysing the current performance. Environmental or sustainable metrics have been embraced because of the growing interest in sustainable VSM in the manufacturing sector (Vinodh, Ruben, and Asokan 2015).

- In the healthcare sector, the manufacturing-like administrative processes share some similarities on the metrics employed to measure production in manufacturing. Patient treatment process focuses performance measurement on the overall process efficiency from patient's perspective (Henrique *et al.* 2016). Therefore, time-relative metrics such as waiting time and the length of stay which can be applied to measure patient care efficiency are widely employed.

- Unlike the manufacturing industry, the construction process focuses more on process variability due to the inherent difference it has when compared to the manufacturing process. As such, performance analysis in the construction industry focuses on measuring work variability to cope with a huge amount of variation and uncertainty in the whole construction workflow (Yu *et al.* 2009).

- In the product development sector, the process efficiency is decided by the quality of information. As such, measuring people involved in the process for the quality of information is highlighted in the product development sector.

- In the service sector, only a fewer metrics have been employed when compared with other four sectors. Similar to the review results in the healthcare sector, waiting time has the highest citations.

4.8.2. Comparison of the Techniques Applied for Future State Improvement

The main focus on the future state improvement strategies is to reduce the seven types of waste (Ohno 1988). Pull system, standardisation, takt time, continuous flow, FIFO lane, and kaizen are the six lean techniques that have been adopted for process improvement across all sectors, especially in manufacturing, healthcare, and construction. In addition, there is a growing interest in management-related techniques (such as early involvement, training, and involvement of stakeholders etc.) in the five sectors. Some techniques such as poka-yoke, total productive maintenance, and heijunka box are rarely implemented. Similar to the metrics used, there are sector-specific findings in the techniques used in VSM, including:

- The manufacturing sector adopts significantly more techniques in process improvement to eliminate waste. For example, takt time has been used by almost half of the published cases as a production rhythm to balance production pace of each value-adding actions in line with final users' requirement. It is noticing that limited lean techniques have been used in the future state map.

- In terms of improving patient flow in the healthcare sector, managerial strategies dominate the waste elimination process. For example, the change of doctors' power and duties (Miller and Chalapati 2015), the adjustment of work sequence (Lummus, Vokurka, and Rodeghiero 2006), and all employee engagement (Henrique *et al.* 2016) are the managerial methods adopted.

- Construction processes focus the improvement on using work restructure and standardisation. As such, critical lean techniques which can be employed to reduce workflow variability in the construction sector are heavily relied upon. FIFO lane (see (Yu *et al.* 2009)) and takt time (see (Rosenbaum, Toledo, and González 2013)) are the two lean techniques that can be adapted to manage the workflow variability.

- Because of the difference of target flows in the process, improving product development processes concentrates on enhancing value-adding activities by increasing communication and interaction efficiency between participants. Lean techniques are merely used in this sector. For example, Tyagi *et al.* (2015) suggested that the deployment of earlier supplier involvement and improved upfront communication in the process are useful to achieve a high degree of correct and proper information. On the other hand, it is interesting to see that some of the VSM research in the product development sector only treat VSM as a single process visual tool. The steps of FSM and Action Plan are excluded. For example, Khurum, Petersen, and Gorschek (2014) used VSM as a performance measurement tool to compare the communication efficiency between the co-located team and a group that was not co-located.

- Similar to the improvement strategies in the healthcare sector, it is found that there are relatively few lean techniques adopted in the service sector. Management improvement strategies are commonly relied upon in the service process comparing to manufacturing.

4.8.3. Comparison of the Benefits of VSM Implementation

Reporting benefits of VSM are of critical importance to improve the uptake of VSM to eliminate waste across all sectors. The reduction of lead time, cycle time and processing time are the most commonly reported benefits in the manufacturing and manufacturing-like production processes.

- The manufacturing sector has a large number of benefit types for production process improvement. The most frequently reported benefits in manufacturing processes are inventory reduction, lead time reduction, cycle time reduction, and manpower reduction.

- Different from the benefits achieved in manufacturing, the achievements of VSM implementation in healthcare administrative processes are related to not only process improvement (see reduced processing time) but also the efficiency of the resources involved in this process (see reduced customer complaints and employees overtime). On the other hand, VSM application aims to reduce the patient waiting time and increase patient throughput in the patient treatment process. Different definitions of value and waste in patient treatment process lead to varied benefits to measure performance improvement (León and Farris 2011).

- In the construction sector, the most frequent benefits mentioned are related to the reduction of lead time, total duration and processing time, which is similar to the manufacturing sector. However, inventory improvement has not been obtained in this sector.

- In the product development sector, as discussed before, not all the articles have provided quantitative benefits. VSM is mainly employed to visualise the process. The integration with other lean tools is only briefly discussed. In addition, because of the differences of the flows in the value stream, the benefits also include the improvement of information iterations in workflows (Tyagi *et al.* 2015).

- In the service sector, although 20% value-added ratio has been obtained (Paciarotti, Ciatteo, and Giacchetta 2011), the benefits of VSM implementations in this sector require further investigation due to limited studies.

4.8.4. Comparison of the CSFs for Effective VSM Implementation

Theory refinement has been identified as a CSF for successful VSM implementation in all the sectors. In the manufacturing sector, theory refinement and integration means that the existing VSM applications are not complete because of the gap between theory and practices (Serrano Lasa *et al.* 2008). For example, VSM is a static image of the value stream, and only the most obvious changes are suggested (Lian and Van Landeghem 2007). In addition, VSM fails to map value streams characterised by multiple flows merging together (Dal Forno *et al.* 2014). Trial and error method, which is employed for continuous improvement to accomplish the desired level of the future state, causes waste of resources (Tyagi and Vadrevu 2015). Therefore, in order to achieve the full functionality of VSM, the incompleteness must be addressed by refining VSM theory and integrating related ideas.

In the other four sectors, the VSM implementation is still in the initial stage, and current research is mainly focusing on how to adapt the existing VSM theory to the specific sectors. It indicates the necessity to apply the lean thinking to accommodate the distinguished characteristics of a sector. In addition, efficient communication and managers' commitment and support to be accepted as important factors of VSM implementation and success. These findings are aligned with Bevilacqua, Ciarapica, and De Sanctis (2016)'s conclusion in terms of lean practice implementation. Some of the sector-specific findings include:

- Employees' involvement in the healthcare sector is considered as an important CSF (Henrique *et al.* 2016). The other notable one is the selection of a project with manageable size (Carter *et al.* 2012).

- Standardisation and training are two important CSFs required in the construction sector because of the features of the construction process.

- Although 18 articles have been identified in the product development sector, few articles discuss the CSFs for successful VSM implementation. It indicates that the discussion of the CSFs is in the infant stage in product development sector.

4.8.5. Causes of the Differences

There may be several reasons leading to the differences in the implementation of VSM in the five sectors.

- Cause 1: unadapted Lean concepts

Not all the lean metrics/techniques provided by VSM theory are available or required in each practical case. One of the reasons that have been mentioned is that some of the concepts need to be refined to improve their usability and practicality (Serrano, Ochoa, and Castro 2008). Another limitation is that all the lean concepts are designed in the context of manufacturing. Not all of them are applicable in the target process (in this case, healthcare, construction, product development, and service). There seems to be an agreement that the lean concepts must be translated to fit the specific practical context. Although a few articles have discussed translating lean thinking to the specific sector context, further discussions are still needed on the critical metrics/techniques that best describe a lean process in various sectors. Thus, there are clear differences on the type or quantity of the metrics/techniques that have been employed in the five sectors.

- Cause 2: inconsistent features of the value streams

A value stream is a series of activities required to bring a product or service from the raw state through to the customer. In the manufacturing sector, the work processes focus on tangible physical product transformation and they are structured and easily to be measured (Rother and Shook 1999). The continuous and transparent production processes make it an easy job to calculate the production performance. Whereas, in the healthcare sector, the service provided during the patient treatment process is intangible and inseparable. The production process may vary for each patient (Poksinska 2010). Similarly, the value streams in the product development sector concentrate on the transformation of information and knowledge (McManus 2005; Tapping and Shuker 2003; Snyder, Paulson, and McGrath 2005). The flow of transferred information is critical in the product development sector (Browning 2003). The service sector shares some of the similar features with healthcare sector, and it is found that its value stream is not a sequential process at all, but rather simultaneous, iterative activities and interactions between buyers and sellers (Barber and Tietje 2008; Moncrief and Marshall 2005). Many studies have also investigated the differences of the value stream in construction projects with the manufacturing sector (Yu *et al.* 2009). The construction process is a complex system that involves tens of trade contractors and consists of hundreds of construction activities. Therefore, the inconsistent features of the value streams among the five sectors may lead to different metrics/techniques. Some of the key concepts used in VSM, such as changeover time, up-time, batch size, takt time, supermarket, and continuous flow are defined in the context of manufacturing and the direct uptake of such concepts in other sectors may be difficult.

Another limitation with the features of value stream is the amount of effort required for data collection. Process invisibility and high complexity make it impossible to collect sufficient data through direct observation in the other four sectors. Not all the metrics/techniques are available for analysing the process performance by considering the features of the value stream. There seems to be a need to investigate the impact of data availability on VSM implementations.

- Cause 3: inconsistent contexts of the flows

Another major difference which may impact the implementation of VSM is related to the definition and characteristics of flow in each sector.

Both physical and information flows in the manufacturing sector are dominated by the tangible process of product production. The production line-driven focuses on eliminating the wastes which have been produced by the inefficient production activities in flows. Value and waste in manufacturing is decided by a simple judgment whether an action contributes to the form, fit or function of the product that customer need– if so, the action is judged to be value-added, otherwise, it is waste of either as necessary or unnecessary (Brown, Collins, and McCombs 2006).

However, without a tangible production process/line, the flows in healthcare and service sectors are not limited to a specific product production, but rather a host of services to deliver a solution to satisfy customers' requirement. Henrique *et al.* (2016) argued that value stream in healthcare sector should involve three flows: information interactions between patients and healthcare staff, the patient transformation process from sick to healthy, and material flows of medication and exam processes. It is argued that one important feature of flows in the wide service processes is that information flow is contributed by employees who deliver the service in the process. As the employee is a fundamental variable in the relationship of service delivery (Leite and Vieira 2015), the production flows are dominated by service processes as well as the interactions between service flows and employees. This finding reinforces the importance of human factor which makes part of the transformation process (Bowen and Youngdahl 1998; Allway and Corbett 2002; Gupta *et al.* 2016). Thus, the flows' efficiency is decided by both the process itself and the performance of people involved. The actions in the lean process aim to eliminate not only the wastes produced by the inefficient process activities but also the wastes caused by the interactions between the process and the human element. This distinct feature also explains why there are often managerial metrics/techniques involved in these two sectors to improve staff involvement and efficient communication.

It has been argued that construction is inherently a site-specific project activity. Limited by the stationary attribute of the building, work flow is characterised as crews of various trades move from location to location (Yu *et al.* 2009; Tommelein, Riley, and Howell 1999). Work flow variability has been recognised as a key constraint of the 'normal' activities in construction processes because of the unique natures of the construction project (Radosavljević and Horner 2002; Thomas and Yiakoumis 1987; Arditi 1985; Choromokos and McKee 1981). The variables involved in work flows are uncertainties caused by the vast resources employed, the unpredictable environment in which construction takes place, and highly interdependences of different parts of the workflow (Radosavljević and Horner 2002; Wang *et al.* 2016). Therefore, unlike manufacturing, where the fundamental problem is overproduction caused by "batch and push" (Womack and Jones 2010), the construction industry suffers from variability. This underlying feature shapes the functions of lean implementation – to create a stable work flow rather than eliminating individual waste.

In the product development sector, value stream is the flow of information and knowledge transferred among the participants. The lean practice aims to improve the quality of iterative deliveries and optimise the activities that produce them (Browning (2003). Under this viewpoint, being lean means selecting the best activities to maximise value and improving the efficiency of information interactions between participants, rather than eliminating waste. Therefore, a correct understanding of the information exchanged, effective accessing of the mutual database, and efficient communication among participants in different stages are the typical issues need to be addressed in product development flows (Tuli and Shankar 2015). As such, most studies emphasised cross-functional integration and collaboration to optimise value flow in the product development sector (León and Farris 2011).

4.9. Summary of VSM Implementation

The implementation level in the manufacturing sector is significantly higher when compared to other sectors. However, process analysis was dominated by lead time reduction with the perspective of increasing process efficiency. Few studies have focused on reducing product defect with the viewpoint of improving process effectiveness. It suggests that VSM tends to be understood as a single tool to visualise the value and waste in processes, rather than as a broader system-wide improvement philosophy. Further research is required on the integration of enhancement strategies.

Lean for healthcare improvement is growing. Studies have contributed to the general understanding of how VSM can be applied to healthcare. However, practical application of VSM is still a challenging task. The review suggests that future developments in this domain should focus on understanding value and waste in the specific process structure, such as defining waste in patient flow, identifying the metrics necessary to measure the efficiency of employee interactions, as well as adapting appropriate lean techniques to healthcare process.

The construction process is considered as a project-driven process of a building. As such, capabilities to manage the variability of the process strongly influence the success of the overall project. Future research should be oriented towards continuing the study of investigating the variability in construction by considering the impact of standardisation on process performance. Another potential future research area is the exploration of a general methodology for defining and classifying construction activities into value adding and non-value adding activities. This will help future studies to develop effective metrics to measure variability as a waste and apply lean techniques in a project environment.

Given that the product development process is considered one of the core information-intensive processes, it is believed that effective communication plays a critical role in this domain to transform data into usable knowledge. Managerial strategies have dominated the lean process development in the reviewed articles. Future research should have a systematic view of VSM implementation with the perspective on both management structure and process re-construction.

In the service sector, there are only two studies on VSM implementation. As such, future studies are needed to explore the applicability of VSM in this sector, followed by the adaptation of VSM in a management-driven environment. In addition, there is a clear need for identifying CSFs of VSM implementations in this sector.

4.10. Summary

VSM has been developed as a systematic theory which can be applied in various scenarios to identify waste and eliminate waste. However, the specific settings in the scenarios may affect the applicability and the effectiveness of the VSM implementation. The review indicates that previous VSM implementations can be classified into five business domains, including manufacturing, healthcare, construction, product development, and service. Each domain has its unique metrics to analyse the current state map and relevant lean tools to achieve an improved future state map. One specific limitation of this study is related to the sampling method. Specific and predefined search criteria were established to include only peer-reviewed publications, although other types of publications may also contribute to the development of VSM theory and implementation. The overall review suggests that there are a number of issues related to the use of VSM which may require immediate attention. These issues identified give hints of the research work need to do when applying VSM in TAM environment.

First, there is a need to address the issue of reference points used in measuring value and waste. The design of applying VSM theory to boost lean thinking application in empirical cases has been the most discussed idea in the literature. A number of lists of value and waste interpretation have been proposed, however, there is no single generally accepted list of unified value-adding and non-value adding time/activities in the specific context. So, how do the current performance evaluation can be conducted if the concept is not properly defined? Understanding what is meant by value and waste and its point of determination in a diverse value stream environment is central to developing solutions for their reduction.

Second, rather than simply focusing on the employment of lean metrics/techniques for identifying and eliminating wastes in processes, it is suggested that there should be a drive toward a conceptual focus to validate the suitability and usability of lean metrics/techniques within the different flow settings. As already indicated, contributions from the value streams and flows analysis in explaining the large differences of lean metrics/techniques employment, peculiarities of value streams and flows in production processes have been recognised as key impediments of the selection and application of lean metrics/techniques. In other words, actions in VSM should focus on what types of lean metrics/techniques should be employed, as well as how the recommended lean solutions should be implemented exactly with the consideration of the production value streams and flows characteristics. Therefore, many of the proposed lean tools/techniques need further validation to confirm transferability to accommodate the distinguished characteristics of a sector.

Chapter 5: Standardising Value Adding and Non-Value Adding Activities in Turnaround Maintenance Process: Classification, Validation, and Benefits

5.1. Introduction

The aim of this chapter is to develop a standardised system to classify VA and NVA activities for lean applications in TAM projects. A comprehensive literature review was conducted on existing methods of defining and classifying value and waste. As a result of this review, an initial standardised system to classify VA and NVA in TAM was proposed, which was then refined through a series of focus group studies conducted with a group of TAM experts. The developed and verified VA and NVA classification system serves as guidelines for effective lean application in TAM projects. A sample case study was undertaken to validate the practicability of the proposed classification system. The classification of the VA and NVA activities is the foundation to identify the value, waste, and its relevant root causes in TAM processes.

5.2. VA and NVA Definition in TAM Project

According to the customer-centreed value proposed by Womack and Jones (2010), project client plays a similar role as 'customer'. TAM is a project initiated by plant operators and executed by professional engineers to ensure multidisciplinary maintenance activities are completed within the strict schedule and limited resources. The successful delivery of projects that meet clients' expectation (i.e. minimised cost, shortest duration, and highest quality) is the main objective of the project (Institute 2000). Meanwhile, the aim of lean maintenance is to improve plant availability and reliability through efficient maintenance. Thus, in this research, value in TAM management is related to the successful completion of the maintenance activities assigned to trade crew. It is related to the maintenance activities that contribute directly to the plant productivity, which include all the physical maintenance operations.

Following Tommelein, Riley, and Howell (1999), the value stream of TAM is the transformation of maintenance activities, which centres upon maintenance staff who move from one functional maintenance to another with the assistance of resources, such as equipment, tools, materials, and information. Accordingly, VA is the group of activities that the trade crews contribute directly to the plant productivity. NVA but necessary includes the group of activities that have no direct contribution to the functions of the plant, but are critical to the maintenance process effectiveness and efficiency. There are two elements in this group: one is the activities to support effective maintenance operation, such as scaffolding erection and crane lifting; the other one is the activities to facilitate process efficiency, such as the required resources and specification that have been delivered/assigned to the right task at the right time. Waste is any activity that represents a potential risk to the plant reliability and maintenance operation efficiency. Improving workflow efficiency ensures that the right task is completed with adequate resources at the right time. In other words, according to the waste definition, waste reduction in maintenance project environment focuses on removing unproductive maintenance work and reducing workflow variability. In TAM project, in order to minimise the loss of production due to plant shutdown, the assumption is that only the imperative tasks are planned and scheduled to ensure the shutdown period is as short as possible. Therefore, it is assumed that unproductive maintenance work is eliminated in the planning phase. The maintenance process evaluation focuses on variation reduction.

Following the definition and understanding of maintenance activities in TAM, a detailed classification of these activities into VA and NVA was conducted.

5.3. VA and NVA Classification in TAM Projects

5.3.1. VA and NVA Classification Development in TAM Projects

Planning and execution of TAM project is a comprehensive management system that involves two levels of maintenance activities according to their relevance to maintenance WPs: maintenance execution activities and non-maintenance execution activities. Maintenance execution activities refer to all the operations conducted to ensure the completion of the maintenance activities in the WP. This type of activities includes all the tool operation, resource support, and safety management activities. On the other hand, non-maintenance execution activities, such as daily prestart meeting, are necessary activities although they are not directly related to maintenance tasks in WPs. As such, there is a need to differentiate the activities based on their relevance to maintenance WPs at the beginning of the classification. The proposed classification aims to provide guidelines for assisting the lean application in TAM projects. The focus of lean improvement is on improving maintenance process efficiency. Therefore, classification in this research is limited to the activities in WPs.

The general VA and NVA definition is not practical to classify the massive amount of activities in TAM projects. Many activities cannot be properly classified because of the lack of clarity of the categories. During the workshop discussions, the classification of VA and NVA were further explained and specific activities were added.

For the classification of VA activities, this subcategory is developed by considering the aim of the activity, which is to improve plant productivity. Based on the aim, the subcategory is the tool activities, which are related to the execution conducted by operation and engineering teams, and includes the main maintenance operations work, such as isolation removal and flange unbolt, physical work on all or part of a plant.

NVA but necessary activities include the critical activities that are conducted to support the effective and efficient execution of the aforementioned tool activities. The activities in this group are further divided into five groups based on their functionalities: including (1) supportive activities for tool operation, which are related to the activities conducted by contractors to support and facilitate the execution of main tool activities. The activities mainly include scaffolding construction and dismantlement conducted by scaffolder and rigger, and lifting work conducted by crane operator; (2) supportive activities for critical resources, which refer to the activities that are performed to deliver/transfer/assign the right resources to the right WPs, such as the essential workers' travel and transportation of tools and equipment on site; (3) critical safety checking activities, which are related to the activities that contributed to the safe execution of maintenance, such as testing, QA/QC conducted by supervisor; (4) critical inspection activities, which include inspection and quality check after the scheduled maintenance; and (5) permit authorisation, which is mandatory before operation. This category is isolated from critical safety checking activities because of its big impact on the maintenance progress.

Waste in TAM projects is largely subdivided into macro-level and micro-level by referring to Han, Lee, and Pena-Mora (2011). The former category refers to waste that is caused by external factors such as weather, or unexpected work scope change. The latter one is by the internal factors of the process, such as unnecessary waiting, moving or inventory which resulted by inefficient resource/process management.

An important underlying assumption for this micro-level waste identification relies upon the recognition of inefficient maintenance execution as well as the factors that can cause variations in an activity. The seven types of waste were identified within the TAM project environment (Table 5-1) by referring to Baluch, Abdullah, and Mohtar (2012), Clarke, Mulryan, and Liggan (2010), and Davies and Greenough (2010)'s research.

Table 5-1: The Seven Types of Waste in TAM Project Environment

The type of waste	Definition in TAM project environment
Overproduction	• Predecessor tool activities are completed in advance, which may result in unplanned execution to avoid waiting, further causing temporally increased resource request, space congestion, or interruption to other relevant activities.
Defects	• Rework or reprocessing, which can cause delay of the succeeding activities, leading to resource idling and poor workmanship.
Poor management of inventory	• Not able to deliver the right material at the right time • Lack of material, tools, and equipment that can cause process delay
Unproductive work	• Unnecessary operations due to poor operation planning • Employees being unfamiliar with operation, causing unnecessary defects
Ineffective data management	• Collecting data that is of no use • Failure to collect data which is vital • Inadequate data updating
Waiting	• Idle time due to any delay in the activities of process transformation, such as the delay due to the unavailability of required resources, including tools and equipment, material, crane, workers and operation permits. • Unnecessary waiting due to poor communication. For example, follow-up activities do not start timely when the predeceasing activity is completed.
Unnecessary motion/transportation	• Any unnecessary travel of the equipment, tool, and labours on site, such as the trips to the workshop, looking for items, moving cranes without good reason.

5.3.2. VA and NVA Classification Improvement in TAM Projects

Frist, a focus group study was conducted to identify any missing activities can be added in and/or misunderstanding of the activities in the classification system. The aim of the classification system is to include all the activities conducted in the turnaround maintenance process at the execution stage. The classification was initiated based on three major turnaround projects, therefore, the classification was not developed for a specific facilities. All possible operations and interactions were investigated.

In the discussion, experts noted that some activities such as crane operation was understood as VA considering its importance in the processes. Hence, the view point of client for the value and waste definition were emphasised.

During the focus group study, some experts use the name of activity as waste. For example, one expert pointed forklift as a kind of waste to indicate the delay or inefficient of such operation. To address this issue, the experts suggested to include the qualifier (e.g. inefficient, excess) of the operation to differentiate value and waste.

Another discussion was the unexpected scope change because of late activity requests. This category includes the added extra jobs due to inefficient planning. This type of operation was not included in the classification system. Experts suggested that this kind of activities have a huge impact to the whole processes. Therefore, all the late activity requests are classified as pure waste to embrace the whole activities in execution.

When comparing the as plan and as-is operation, it is clear to see not all the planned activities are completed. Experts suggested that an incomplete category of waste was proposed to include missing or incomplete operations.

When the activities were teased out. The second focus group study was conducted to exam the taxonomy of the classification system. During the focus group discussion, the experts noted that the value or waste resulted from the complex interfaces were extremely important for the successful completion of TAM projects. Experts considered that the TAM activities can include both maintenance and information flows. It was proposed that the categories of the classification system should be separated into maintenance activities and relative administrative support considering the impact of interface complexity among the maintenance execution. Administrative activities aim to assist the interaction between site operation and senior management. One of the examples of this type of activities is progress updates and handover in tool activities.

Another discussion was the different classification of the activity of daily safety report. It has been classified into different value category because both scheduler and safety check have this type of activity in their work log. This difference was removed by assorting this type of activity to safety checkers.

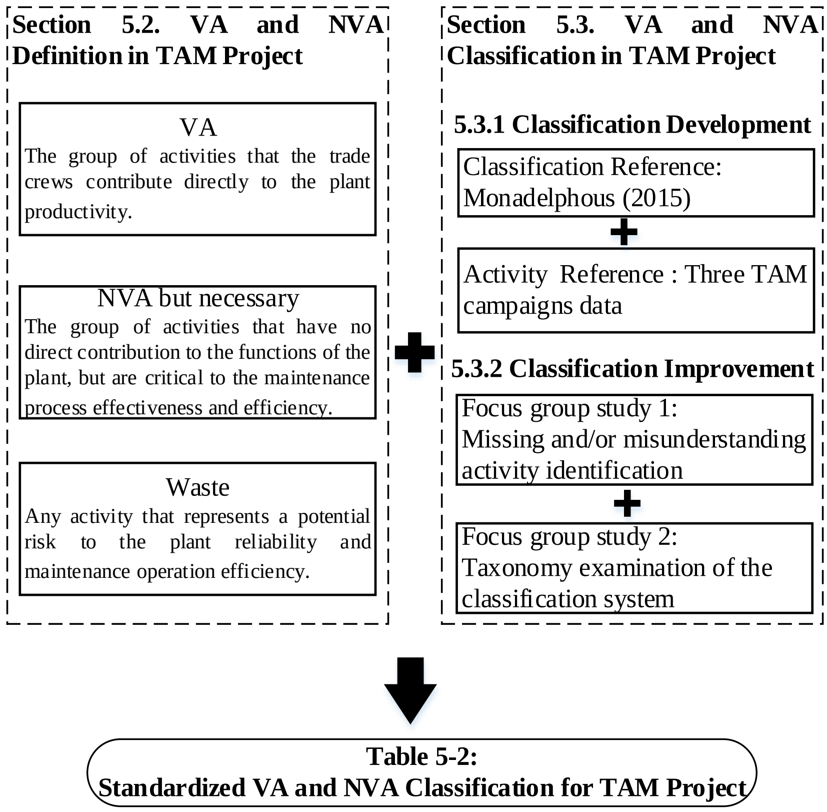

Figure 5-1: The Process of Standardised VA and NVA Classification Framework Development for TAM projects

As shown in Figure 5-1, the redefined VA and NVA are the theory foundation of the classification. The classification was developed by referring to the framework proposed in Modadelphous (2015). Three TAM campaigns are the database used for identifying activities in TAM projects. Two focus group studies were conducted to improve the initiated framework. Table 5-2 shows the standardised Standardised VA and NVA Classification for TAM Project.

Table 5-2: Standardised VA and NVA Classification for TAM Projects

Category	Level 1	Level 2	
		Maintenance activities	Administrative activities
VA	Main tool activities	• Engineering operation (on-site) - Engineering operator • Engineering operation (off-site) - Engineering operator	• WPs sign on/off – superintendent • Operation sign on/off – supervisor • Progress update and handover – supervisor • Daily progress update - scheduler
NVA but necessary	Supportive activities for tool operation	• Erection, modification or dismantlement of temporary structure (i.e. Scaffolding) - scaffolder	• Communication between supervisor and scaffolder
		• Preparation, operation or dismantlement of lifting and rigging: - Crane operator	• Communication between supervisor and crane operator, rigger and dogman

Category	Level 1	Level 2	
		Maintenance activities	Administrative activities
		- Rigger - Dogman	
	Supportive activities for critical resources	• Logistics for labour - Workers' travel to/from site	• Communication between supervisor and contractors • Electronic data compiling – administrator
		• Logistics for equipment/tools transportation - Tools transport to/from warehouse - Equipment transportation	• Communication between supervisor and material office/storeman • Electronic data compiling – administrator
		• Logistics for material transportation - Material transportation to laydown area (on site) - Material transportation for refurbishment (off-site)	• Communication between supervisor and truck drivers • Progress update and handover – supervisor • Communication between supervisor and off-site supply chain • Electronic data compiling – administrator
	Critical safety checking activities	• Safety check of clean, inspection and measurement - inspector	• HSE data collection and record – inspector • Risk assessment report – supervisor

Category	Level 1	Level 2	
		Maintenance activities	Administrative activities
			• Communication between supervisor and HSE inspector
	Critical quality inspection activities	• QA/QC – QMI technician - Alignment/measurement check	• QA/QC sign on/off – supervisor • Communication between supervisor and inspector/QMI technician • Electronic data compiling - administrator
		• QA/QC - QMI technician	
		• Testing - inspector	• Testing sign on/off - supervisor • Testing record - inspector • Electronic data compiling - administrator
	Permit authorisation	• Permit sign on/off - supervisor	• Permit record – supervisor • Communication between supervisor and permit manager

5.4. Validation by Industry Experts

The interview in the third focus group study results in terms of the epistemological adequacy and reusability are shown in Table 5-3. The responses on epistemological adequacy (Q1-Q4) were generally positive. All the mean scores are higher than 4.5, which means interviewees confirmed the epistemological adequacy on the aspects of clarity, intuitiveness, relevance, and completeness. The standardised classification of the TAM activities can assist lean thinking and implementation in TAM projects.

The mean score of Q1 (4.5) and Q2 (4.7) indicate that all the interviewees agreed that the detailed classification of the activities in each category is adequacy as all the activities are classified based on two dimensions: the content and the executor of the activity. Therefore, the activities can be precisely recognised by referring to the two aspects. As mentioned in the Section 3.2.1, the activities used for the development of the classification were from three different TAM projects. The mean score of 5.3 of Q3 indicates that the investigated three major turnaround projects ensured the relevance of the activities. In addition, the 4.5 score of Q4 indicates the size of the database ensured the completeness of the activities. However, the interviewees pointed out that only the activities in operation schedule and workpackages are considered in this study. Some activities beyond the boundary might be identified when undertaking a complete process review. It is recommended that a clear boundary should be set up prior to the activity analysis.

As can be seen from Table 5-3, the mean scores 5.2 of the project type of reusability (Q5) show that the proposed classification system is suitable for all types of turnaround projects in the oil and gas industry. The maintenance planning and execution in valve replacement and compressor overhaul are desirable to use this classification system. It was also pointed out that the understanding of VA and NVA was from clients' perspective. The activities that contributed to the maintenance process effectiveness (e.g. scaffolding, crane work) could be categorised as VA from the viewpoint of contractors. In future research, the classification system should consider various viewpoint, such as operation contractor and resource vendors.

The domain reusability (Q6) with a score of 5.0. Interviewees were cautious about the usability of the classification system in TAM projects in addition to oil and gas plants. The understanding of value, VA and waste might be similar in project-based maintenance execution in domains such as power plant and airport. However, the proposed classification system was developed based on maintenance features and types of tasks that were partially unique to TAM. For example, oil and gas plants are usually located at remote area and resource availability is a big concern in this type of project. This specific feature explains why the waste caused by resources availability was highlighted.

Table 5-3: Interview Results Regarding Epistemological Adequacy and Reusability of Classification

	Question	Mean
Epistemological adequacy	Q1: Do all concepts and relations in the classification system have clear and unequivocal meaning?	4.5
	Q2: Does the classification system provide a vocabulary that matches the intuition of the experts?	4.7
	Q3: Are all the concepts in the taxonomy relevant for the domain?	5.3
	Q4: Does the classification system cover all relevant concepts that may be relevant to any task, activities?	4.5
Reusability	Q5: Is the classification usable for all types of TAM project in oil and gas industry?	5.2
	Q6: Is the classification dependent on certain types of domains?	5.0

The reliability was investigated by interviewing six participants. Interviewees suggested that the implementation of this classification system in real practice can work alongside with the existing delay card system. The delay card is the delay tracking system to record delay information and quantify the wasted production time because of delay. It is argued that the current delay information tracking and quantification were not structured and it is therefore difficult to analyse the reasons behind the delay. The standardised classification system provided a reference to standardise the categories of the delay. It can help reduce the time spent for delay identification.

The appropriateness of the classification was checked by adopting the Kappa statistic. As shown in Table 5-4, the result 0.96 indicates an almost perfect agreement. The standardised classification system was accepted by all participants, who agreed that the proposed classification system can be used to analyse the productivity of the maintenance process.

Table 5-4: Kappa Test for Results of Classification Reliability

Item	Result
Number of activities	20
Number of interviewees	6
Observed agreement	0.89
Expected agreement	0.72
Kappa	0.96

One sample case was used to examine the potential use of the proposed classification system in practice. As explained above in Section 3.3, Table 5-5 shows the results of the distribution of the VA and NVA by using the standardised classification system.

Table 5-5: VA and NVA Cclassification by Using Standardised Classification Systems

Category	Level 1	Level 2	
		Maintenance activities	Administrative activities
VA	Main tool activities	Isolate/disconnect - INLEC Break flange – valve mech team/Ops Remove valve – valve mech team Fit blind – valve mech team Drain decontaminant - operations	Daily progress documentation – schedule coordinator Daily progress documentation – logistics
NVA but necessary	Supportive activities for tool operation	Preparation, operation or dismantlement of lifting and rigging: - Crane operator	Communication between mech team and crane operator
	Supportive activities for critical resources	Too and equipment requirement, searching and transportation – operations Packing – general service	Communication between mech team and INLEC team Communication between mech team and general service

Category	Level 1	Level 2	
		Maintenance activities	Administrative activities
		Truck supply for workfront – logistics Onsite transportation – logistics Offsite transportation – logistics	Communication between mech team and logistics Communication between coordinator and off-site supply chain Communication between coordinator and truck drivers
	Permit authorisation	Issue permit – operations Permit sign on - operations	Permit record – supervisor Communication between schedule coordinator and permit manager

According to the proposed classification system, the analysis reveals that:

- The tool activities of isolation, break flange, valve removal, fit blind and drain decontamination conducted by professional principles have been identified. The administration activities to support tool operation were classified as well, which include Daily progress documentation conducted by schedule coordinator and logistics respectively.

- NVA but necessary activities have been identified as well. The supportive activities for tool operation include crane operation in the selected sample. The activities of logistic are the supportive activities critical resource. The communication between mech team and crane operator was defined as administration activity in this group. The operation required for the on-site and off-site transformation of material were classified into supportive activities for critical resources. The essential communication between difference groups were the administration activities to support such kind activities. Permit authorisation include the activity of issue permit conducted by operation staff. Administration activities in this group include the record of all relative permit operation.

- There is one deviation has been observed. The minor difference is caused by the different classification of the activity of daily safety report. It has been classified into different value category because both scheduler and safety check have this type of activity in their work log. This difference was removed by assorting this type of activity to safety checkers.

From the analysis, it can be concluded that different types of operations were considered within each category of the classification system, different activities were defined according to the two dimensions of operator and operation. It is revealed that the understanding and classification of value and waste in this research can be used to classify VA and NVA.

5.5. Summary

In this chapter, a classification system of VA and NVA that can affect the lean application in turnaround projects in the oil and gas industry was developed. This chapter defined the activities of VA and NVA by adapting the manufacturing setting to a TAM setting through a practical and structured approach. Additionally, the activities conducted in TAM projects were identified and classified to align with the proposed definition of VA and NVA. The maintenance activities and relevant interactions and communications in TAM process were coved in the classification system. The initiated classification system was improved by two focus group study at first, and then validated by undertaking structured interviews. The validation processes indicated that the classification system follow the lean philosophy. The usefulness of the system was demonstrated in a valve replacement project in TAM. The case study revealed that the proposed classification system can provide precise classification of value and waste in both maintenance operation and information flows. The contributions of this chapter are summarised as follows:

(1) the development of a standardised classification system that can facilitate the application of lean philosophy and the development of lean strategies to remove waste in TAM setting; and (2) increased accuracy of the distribution and percentages of waste in each type of maintenance activities, which leads to a higher performance level of TAM project management in oil and gas industry.

Chapter 6: An Enhanced VSM Framework for Improving TAM Process Efficiency

6.1. Introduction

The aim of this chapter is to develop an innovative Enhanced-VSM framework for a structured application of VSM in turnaround process. With the full consideration of the prerequisites of VSM application, project characteristics, the unique nature of turnaround process, and the challenges that impede the application of VSM in the turnaround process were identified. In order to tackle the challenges, a conceptual framework for facilitating the VSM implementation in TAM projects is presented. The enhancements are presented in the following sections.

6.2. A Framework of Enhanced VSM

Figure 6-1 shows the Enhanced-VSM framework, including five steps:

- Step 1: Critical work scope selection
- Step 2: Current state mapping and measurement
- Step 3: Waste analysis
- Step 4: Future state improvement
- Step 5: Action Plan

The five-step enhancement framework is a continuous improvement loop to minimise the waste. It provides guidelines on streamlining the maintenance process in TAM projects, with an objective to minimise waste and maximise planning and control efficiency.

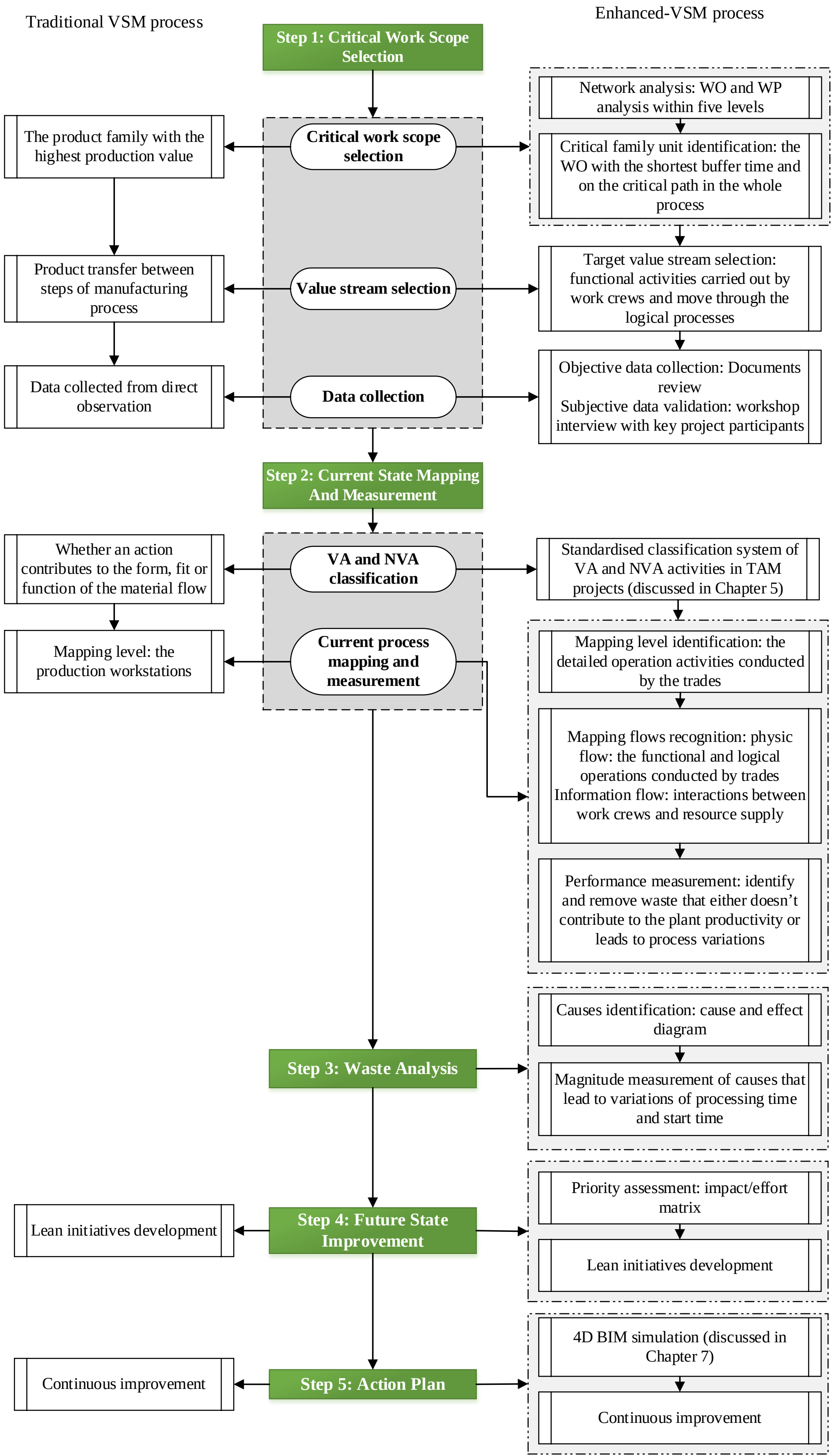

Figure 6-1: The Framework of Enhanced-VSM

6.2.1. Step 1: Critical Work Scope Selection

The purpose of the first step is to select a critical work scope for current state mapping. Critical work scope selection is one of the most important factors for successful lean transformation. There are three processes within this step.

- Network analysis. The analysis provides the details and logic of WOs and WPs in one TAM project.

- Critical family unit identification. Product family is a group of products with the similar production process, it is the standard unit for VSM analysis (Rother and Shook 1999). A TAM project usually consists of several WOs. The maintenance activities in each WO are generally planned in a relatively independent way. According to this rule, the one or several WPs involved in the same WO can be regarded as one operation family. The target product family is the WO with the shortest buffer time in the planned schedule and it usually plays critical role (i.e. is on the critical path) in the whole process. In other words, it is the WO that has the highest risk of delay. If there is more than one WPs included in the product family, the critical family unit is the WP which has the longest scheduled operation time.

- Target value stream selection. Value stream is a series of activities required to bring a product or process from raw state through to the customer (Yu *et al.* 2009). In TAM project, value stream can be considered as a group of functional and logical activities carried out by work crews to complete the maintenance work. The selection of target value stream under the critical family unit follows the criteria: (1) manageable: an execution process that consists of a number of "governable" activities; (2) meaningful: the selected workflow is critical in the tight schedule, in other words, they are on the critical path.

- Data collection. Data collection follows the rules proposed in Section 3.4.2. In order to enhance the reliability and validity, data is collected from (1) a comprehensive review of the documents of the selected maintenance project; and (2) VSM development workshop with key participants.

6.2.2. Step 2: Current State Mapping and Measurement

The second step is related to the development of the current state map. In TAM project, process mapping is a detailed level of description of a maintenance workflow. Workflow analysis focuses on exploring answers in terms of value creation and value evaluation in the TAM environment. Such analysis has three objectives: (1) to clearly define and classify the VA and NVA in TAM workflow; (2) to identify activities in critical value stream; and (3) to develop feasible measurements for workflow performance measurement. There are three processes in this step.

Process 1: Definition and classification of VA and NVA in TAM workflow. The aim of this process is to develop a standardised system to classify VA and NVA activities for lean applications in TAM projects. First, value and waste have to be redefined in the maintenance project environment. Second, the VA and NVA classification is developed by taking into account the peculiarities of turnaround project in oil and gas industry. The detailed development has been introduced in Chapter 5.

Process 2: Mapping the maintenance execution process. There are two considerations in the mapping process, including mapping level identification and mapping flow recognition. First, the level of mapping is the identification of functional units. Functional units in the mapping are the information boxes which indicate the detailed production information. In manufacturing, the production process in a target value stream is drawn at floor level and shown by the production workstations. In TAM projects, the workflow during the turnaround maintenance is related to the execution process that consists of relevant maintenance activities conducted by trade crew. Therefore, the functional units of in the mapping process are related to the detailed operation activities conducted by the trades.

The flows in current state map are related to both material and information in a value stream. In TAM projects, the flows may include the work crews, information, material, tools, equipment, and transportation flows. The lead time of the maintenance execution not only depends on the effective flow of trade crews operation by considering resources such as material, tools and equipment, and information, but also the efficiencies of flows to meet the maintenance needs. Accordingly, the physical flow is the functional and logical operations conducted by trade crew to complete the maintenance effectively. While the information flow is the interaction between the operations and resource supply which has potential impact to the operation efficiency.

Process 3: Performance measurement is related to demonstrating how value is evaluated and what types of waste can be identified. Based on the value and waste definition in Chapter 5, the management of workflow aims to identify and remove waste that does not contribute to the plant productivity or lead to process variations. The variables in a TAM project include weather, work process, material supply, workers availability, neighbouring maintenance activities, the required resources, locations, etc. The main assumption is that TAM project productivity and performance could be improved by reducing the variations in the process.

Based on the objectives of process improvement in TAM project, the performance of the TAM execution process is measured by using the following metrics. First, the basic lean metrics of lead time (LT), and cycle time (CT) are measured. The value of LT (or CT) in planned and actual operation are compared. The value of extended project duration and the value of extended execution time proposed and calculated by the following equations:

Extended project duration = LT in actual process – LT of planned schedule

Extended execution time = sum of CT in actual process – sum of CT in planned schedule

Two metrics are also proposed to measure the variations in the process: processing time variation and start time variation. These two metrics have been adopted by Wambeke, Hsiang, and Liu (2011) to study the variations and relevant causes in construction projects. The processing time variation is the difference between the planned and actual processing time. The start time variation is the difference between the planned and actual start time. Each activity in value stream is examined to identify the waste caused by either extended execution time required or the challenges that may affect the starting time. The metrics are calculated by the following equations:

Processing time variation = actual process time – planned process time

Start time variation = actual start time – planned start time

Table 6-1 shows the key metrics used to measure the effectiveness and efficiency of TAM execution process.

Table 6-1: Key Metrics for TAM Process

Metrics	Unit	definition
Lead time (LT)	Minutes	The time that elapses from the start to finish of maintenance execution of the whole processes
Cycle time (CT)	Minutes	The time that elapses between one unit get finished to the next unit get finished
Processing time (PT)	Minutes	Duration between the finish time and start time of an activity

Metrics	Unit	definition
value-adding time (VAT)	Minutes	The sum of PT of the VA activities in processes
Processing time variation (PTV)	Minutes	Difference between planned and actual processing time
Start time variation (STV)	Minutes	Difference between planned and actual start time
Rework	%	rework time / processing time

6.2.3. Step 3: Waste Analysis

Step three is related to waste analysis, which aims to identify the root causes of the variations in the workflow. The concept of root cause analysis, which aims to investigate the schedule and the utilisation of all relevant resources to reduce variations, is the fundamental idea behind this approach. There are two processes in this step.

Process 1: determining the causes that lead to variations. In order to systematically study processing time and start time variation, a cause and effect diagram is constructed and used to identify the causes of variation for each activity. A cause and effect diagram is a method invented by Kaoru Ishikawa in 1963. As shown in Figure 6-2, the chart is a graphical representation of potential causes of a certain undesirable effect, i.e., variation in this study. The possible reasons for variation are investigated from six categories, namely, system, environment, process, equipment and tools, labour force, and materials and components. The six categories are briefly introduced below.

- System. It refers to the planning quality of WP, including:
    1) the strict specification/method in WP
    2) the complexity of the activities in WP
    3) constructability of the activities in WP
- Environment. It refers to a broad setting of the TAM projects and includes:
    1) External conditions: weather changes that might impact maintenance execution
    2) Internal job site: the availability of workspace to perform maintenance tasks

(accessibility, site congestion)

3) Internal location condition: the efficiency of the work conduction

- Process. It refers to identify the reasons that result in inefficiency in both physical and information flow, including:

1) Prerequisite work: the work has to be completed before starting the following activity, which includes:

   - the completion of the previous activity (completed in advance, delay due to rework or poor quality)
   - the QA/QC inspection of previous activities
   - the required permit to start the work

2) Information flow, including:

   - Coordination between trade crews
   - Coordination between superior and subordinate (e.g. supervisor and project manager)
   - Instruction from supervisor

- Equipment and tools. The availability of equipment and tools to assist in the efficiency maintenance execution. The equipment and tools include:

1) Crane or forklift
2) Rig
3) Truck
4) Other equipment
5) Hand tools
6) Personal protective equipment (PPE)

- Labour force. The availability of men power has an essential impact on the efficient maintenance execution, including:

1) The efficiency of labour's operation (experienced, lack of skill, new employee)

2) Arrive late to conduct the activities

- Materials and components. The efficiency of materials and components to finish the activities, including:

1) Movement or transportation of material between site and store yard

2) Arrival of material from suppliers

3) The size of required materials and components

4) The type of required materials and components

This study focuses on a graphical presentation to illustrate the identified causes of each variation respectively. Focus group study is adopted to construct the process of analysis. The chart itself is a tool for facilitating participants to identify causes.

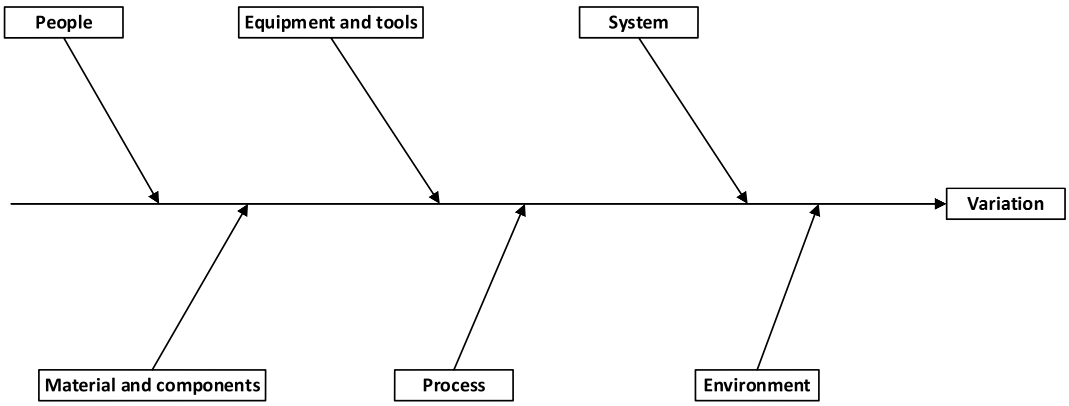

Figure 6-2: Causes and Effect Diagram

Process 2: determine the magnitude of the causes that lead to variations of processing time and start time. The identified causes of variations are quantified based upon the magnitude of the variation (measured in hours). In order to identify the most significant causes, all causes in the process are ranked. The top 10 causes are identified.

6.2.4. Step 4: Future State Development

The fourth step in the enhanced-VSM framework is the development of the FSM for the critical value stream. The focus is to optimise current maintenance process by selecting and adapting appropriate and relevant lean tools to eliminate the specific waste. FSM has two processes.

Process 1: priority assessment. The assumption in TAM projects is that the capacity for waste elimination actions is limited due to its complexity and scale. Therefore, all the causes of variation cannot be eliminated simultaneously and a need for prioritisation is warranted. An impact/effort matrix is therefore development with the involvement of key participants to prioritise the causes of variation (see Figure 6-3). The impact/effort matrix is a tool to evaluate several options by considering both the impact a variation and the required effort to solve the issue. It is a favourite tool for prioritising the options when objective data is not available. In this matrix, the impact is illustrated in five levels, from low, minor, moderate, major, to catastrophic. The effort is classified as rare, minor, moderate, great, and tremendous. The resulting prioritisation, illustrated as low (L), moderate (M), high (H) and extremely high (E) in Table 6-2. The improvement will start from the variations which have extremely high priority.

Table 6-2: Impact/Effort Matrix

		Effort				
		Rare	Minor	Moderate	Great	Tremendous
Impact	Low	M	M	L	L	L
	Minor	H	H	M	L	L
	Moderate	**E**	H	H	M	L
	Major	**E**	**E**	H	M	M
	Catastrophic	**E**	**E**	**E**	H	M

Process 2: Lean initiatives development. The focus of process improvement in TAM project is limited to improve workflow stability by reducing variations. The lean initiatives that can be applied are highly depended on the findings of the prioritised causes of variation. The lean initiatives development will be proposed and developed depending on the specific cases.

6.2.5. Step 5: Action Plan

The last step is the development of an Action Plan to resolve the identified issues. In order to explore the potential impact of the application, the planned changes are estimated in a virtual environment before actual implementation. Information technologies, including Building Information Modelling (BIM), are applied to explore the opportunities for assisting lean application.

6.3. Case Study

6.3.1. Target Value Stream Selection

Following the enhanced-VSM framework, 18 WOs have been identified. Valve replacement is the target product family has been selected. This is because valves installation and removal wasn’t completed in the planned sequence in allot of cases. Meanwhile, little float time has been assigned to the planned schedule to absorb the possible variations, and 74 hours excess lead time have been observed by comparing the planned and actual production. There are 100 valves in the value replacement WO which need to be removed, refurbished, and installed. The conventional approach to planning maintenance execution is Gant Chart. The maintenance starts from one valve and then continued to the next in a simple upward progression. The maintenance activities for each valve replacement follow on another in a linear way. The scheduling approach of using a Gant Chart aims to achieve the shortest duration. The first valve for removal/refurbishment/installation was delivered on day 6 and the maintenance of all 100 valves was completed on day 14. Commissioning, a quality assurance process to make sure the repaired, overhauled or replaced facilities ready to service, was conducted when all the valve maintenance work have finished. The total duration for the valve replacement (including the period of commissioning) is 18 days. The maintenance process of one valve replacement was the target value stream to quantify the process performance.

Basic maintenance data was collected by researchers using the proposed method and then verified by focus group discussion. However, to maintain confidentiality, the data sets and the obtained results have been modified. Table 6-3 shows the indicators used in target value stream.

Table 6-3: Indicators Measured in Target Value Stream

Indicators	Unit	definition
Start time	Minutes	Start time of the activity
Finish time	Minutes	Finish time of the activity
Number of Workers	Unit	The number of workers involved in the activity
Time of rework	Minutes	The time of rework conducted by workers

6.3.2. Current State Mapping and Measurement

A current state map was developed. The maintenance workflow involved three stages: on-site valve removal, off-site refurbishment, and on-site valve installation. A total of 422 activities were identified and analysed from this case. The replacement of the 100 valves followed a similar process and most of the actions are repetitive. Finally, 42 activities were screened out after repetitive activities were removed. The effectiveness of the proposed classification system was evaluated by using the standardised classification system to measure the VA and NVA. Figure 6-3 shows the TAM process flow chart (stage 1-3).

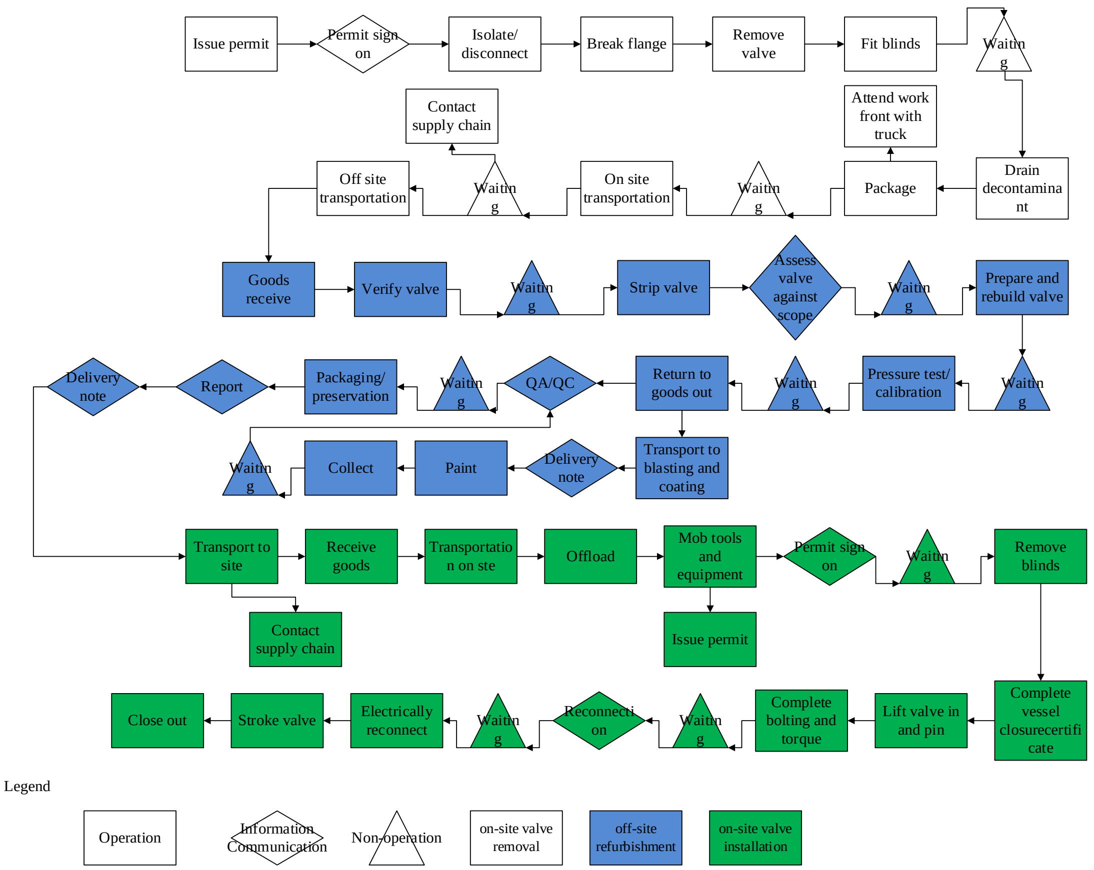

Figure 6-3: TAM Process Flowchart (Stage 1-3)

The three stages were mapped and analysed. Figure 6-4 shows the main flows of valve replacement. Schedulers and superintendents from the client are the centres of execution control. They are responsible for coordinating the work flows in the process and issuing execution permit for the work with the view of quality assurance and risk estimation. The mapping of the value stream made it possible to evaluate the inefficiencies of valve replacement (Figure 6-4a, b, c).

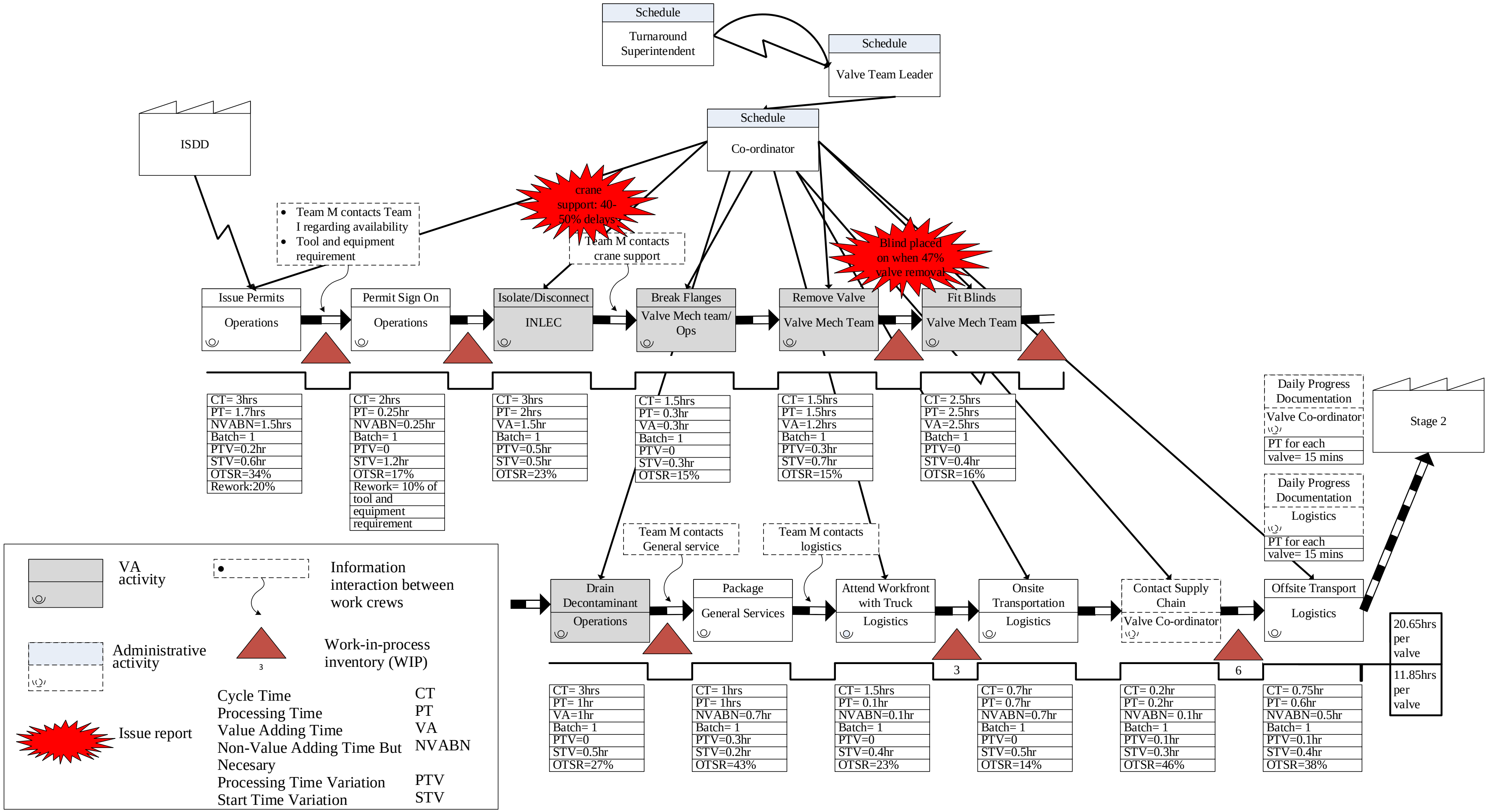

Figure 6-4a: Current State Map of Valve Replacement – Stage 1

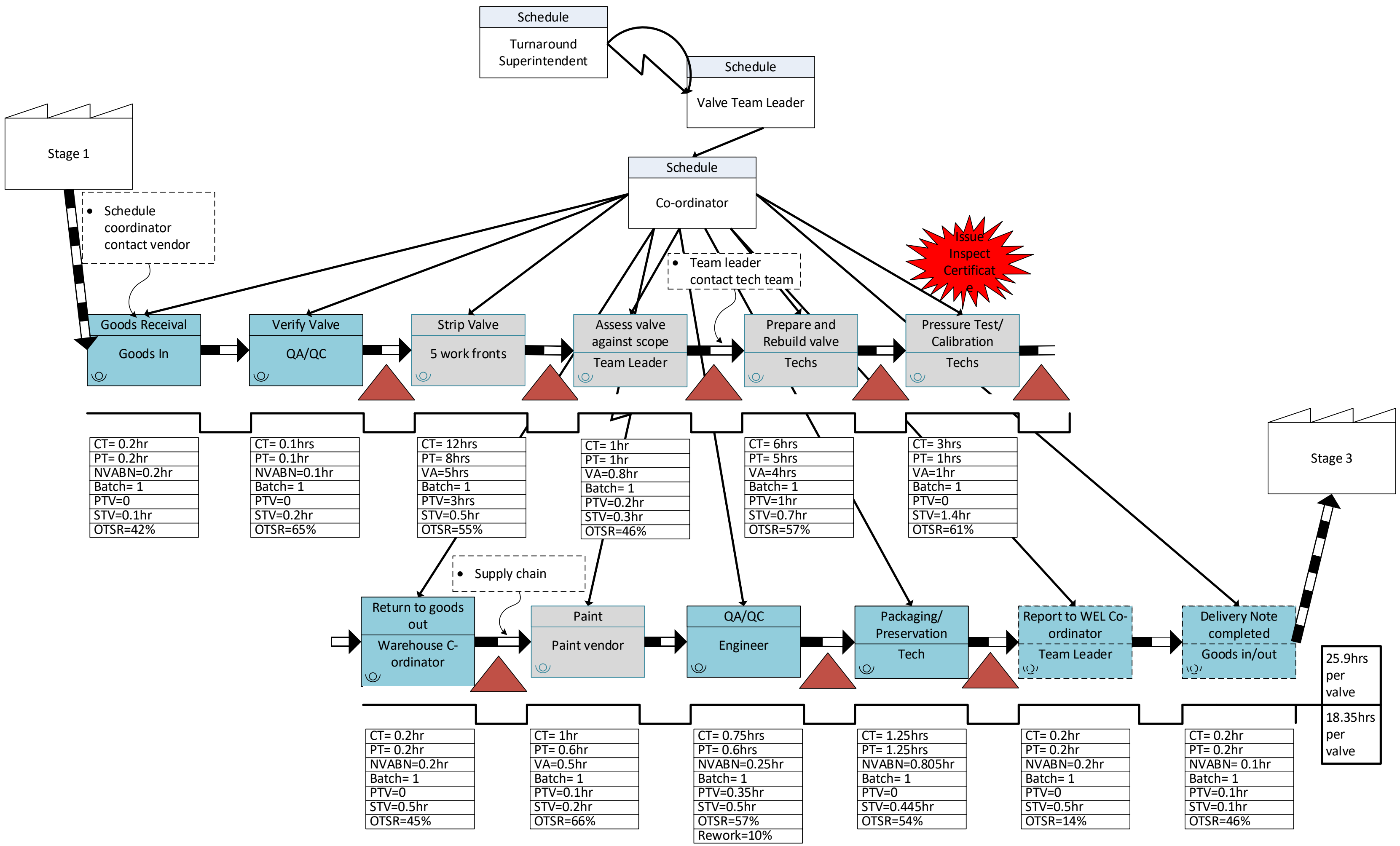

Figure 6-4b: Current State Map of Valve Replacement – Stage 2

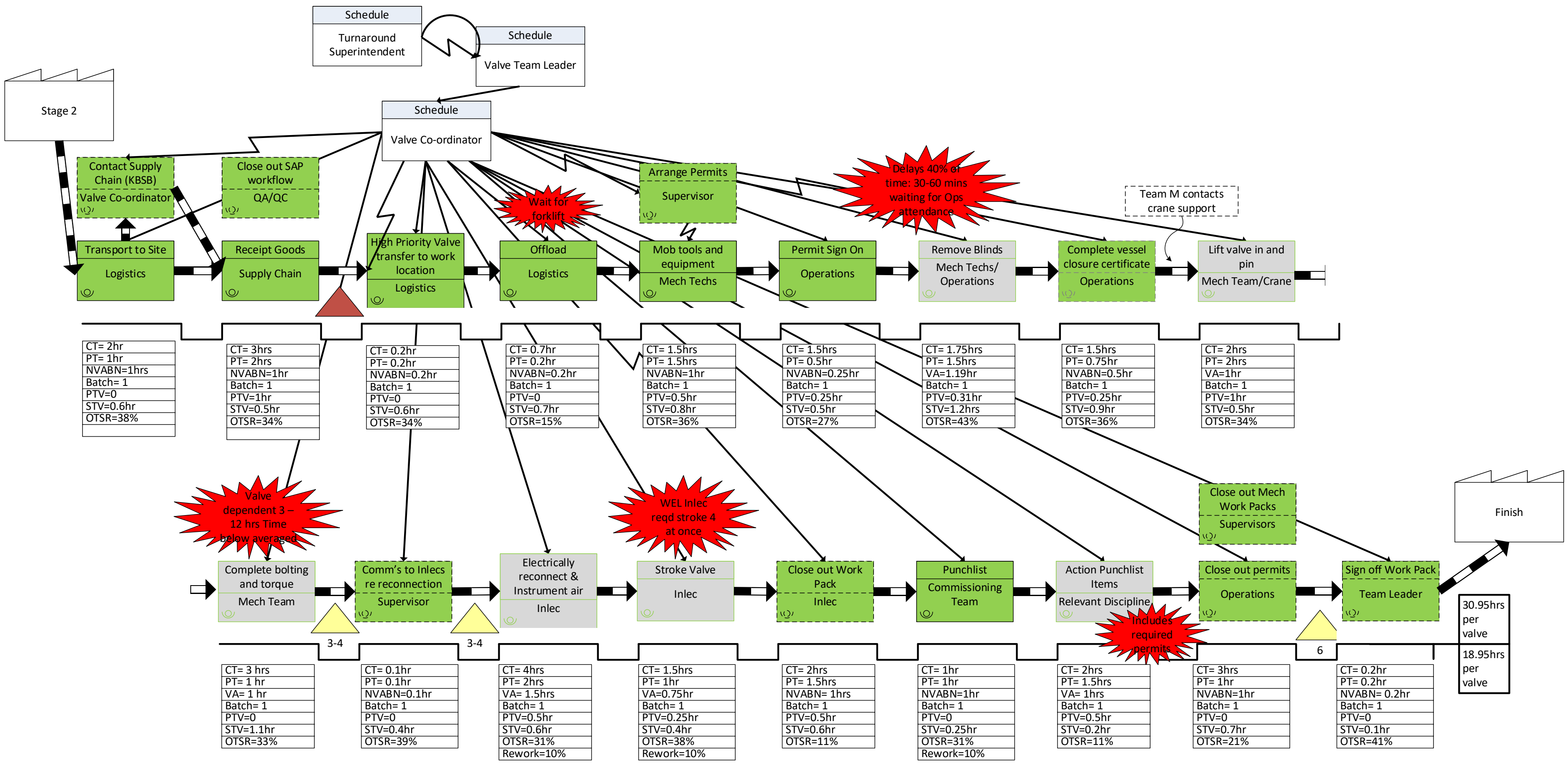

Figure 6-4c: Current State Map of Valve Replacement – Stage 3

Upon quantifying the performance of the current state by using the metrics proposed in Table 6-1, several wastes can be identified immediately. The average processing time for one valve in the actual process is 49.15 hours, exceeding the planned processing time 11.755 hours. The total amount of actual cycle time is 77.5. A difference of 28.35 hours difference between cycle time and processing time has been quantified. A number of observations can be obtained from Figure 6-4a, b, and c.

Variability of the maintenance execution within activity

In this case, the first observation was the waste reflected by the great dispersion of the cycle time recorded. Unlike the constant data collected of the processes in manufacturing, the cycle time of maintenance activities conducted on each valve has a huge variation. In order to simplify the analysis, the average values of cycle time and processing time for the valve processed in the value stream are shown in the data box. For example, the cycle time of break flanges varied from 134 to 65 mins, with a mean of 90 mins. This clearly shows that valve replacement was not a standardised and continuous process.

The second observation is the great variations observed in the processing time and cycle time. Map shows the great differences of the processing time used and the cycle time that the activities were taken. For instance, the processing time for break flanges is 18 mins, while the cycle time is 90 mins (as shown in Figure 6-4a). 72 mins differential have been observed. It can be explained by a number of factors, e.g. the delay caused by material/equipment/tools supply, the idle of the workers on site, rework happened, or the changes in process. The detailed investigation will be presented in Section 6.3.3.

Huge variations of start time and processing time

The third observation is the waste presented in the analysis of variations. Schedule compliance was indicated by the metrics of variations of processing time and start time. First, the data shown in current state map indicated huge variation of start time. The value of start time variation revealed that most of the processes have suffered from various degrees of delay to start. The analysis also showed that the activities executed have a large tendency of delay to start work on time. The on time start rate of the activities conducted in the same process was measured. The percentage of on-time start activities is relatively low, especially for activities which were conducted at the first stage. For example, the percentage of on-time start for break flanges is 11%.

Second, the variation of processing time. The processing time recorded in the current state map is the actual processing time have taken, the VA and NVABN time is the planned processing time for each process. The difference of the two values indicates the excess processing time. The data recorded show big variations, the values of difference indicated that most activities suffered longer processing time.

Low VA percentage

The last observation is the relatively low VA percentage in the process. According to the definition and classification proposed in the enhanced-VSM framework, the VA activities in the process were highlighted with the grey color background. The results show that only 49.33% of the processing time added value to the maintenance execution. 26.77% of the total processing time was categorised as NVA but necessary activities. In addition, 23.92% of the excess processing time was identified as waste. A total of 28.35 hours excess cycle time was recorded as waste. Table 6-4 shows the performance of the targeted value stream.

Table 6-4: The Percentage of VA and NVA

	Maintenance Execution	
Classification	Hours	Ratio
VA (PT)	24.24	49.33%
NVA but necessary (PT)	13.15	26.77%
Waste (PT)	11.75	23.92%
Waste (CT)	28.35	-

In summary, the existing process exhibited various forms of waste, great dispersion of the cycle time, great variations between cycle time and processing time, huge variations of starting time and processing time. Based on the analysis of current practice, the aim of lean improvement for the TAM projects was set as increasing operation efficiency by stabilising the process, and eliminating variations, shortening the gap of cycle time and process time, reducing the lead time of the project.

VA and NVA analysis for each stage

Meanwhile, the current state at each stage was analysed respectively. The performance of current process were elaborated by classifying VA and NVA activities according to the standardised classification system. The efficiency was measured by quantifying the VA and NVA activities, and waste.

- Current state analysis for Stage 1

Stage 1 was related to vale removal. There are 12 processes in stage 1. The classification of VA and NVA but necessary for both maintenance and administrative activities were elaborated in Table 6-5. There were five main tool activities and seven NVA but necessary activities in the current process. The relevant administrative activities to support the maintenance activities are also shown in Table 6-5.

Table 6-5: The Classification of VA and NVA but Necessary Activities in Stage 1

Category	Level 1	Level 2	
		Maintenance activities	Administrative activities
VA	Main tool activities	Isolate/disconnect - INLEC Break flange – valve mech team/Ops Remove valve – valve mech team Fit blind – valve mech team Drain decontaminant - operations	Daily progress documentation – schedule coordinator Daily progress documentation – logistics
NVA but necessary	Supportive activities for tool operation	Preparation, operation or dismantlement of lifting and rigging: - Crane operator	Communication between mech team and crane operator
	Supportive activities for critical resources	Too and equipment requirement, searching and transportation – operations Packing – general service Truck supply for workfront – logistics Onsite transportation – logistics Offsite transportation – logistics	Communication between mech team and INLEC team Communication between mech team and general service Communication between mech team and logistics Communication between coordinator and off-site supply chain Communication between coordinator and truck drivers

	Permit authorisation	Issue permit – operations Permit sign on - operations	Permit record – supervisor Communication between schedule coordinator and permit manager

As shown in Table 6-6, the total cycle time at Stage 1 was 20.65 hours and the processing time was 11.85 hours. 6.5 hours were categorised as VA. Similarly, 3.85 hours were categorised as NVA but necessary. 1.5 hours process time variation (excess processing time) and a difference of 8.8 hours between the cycle time and the processing time were observed and need to be analysed. Some of the reasons that lead to variations were listed in the current state map, such as the 10% rework at the process of Permit Sign On because of tool and equipment requirement. In addition, 40-50% delay of the crane support was reported at the process of Break Flange. Increased work-in-process inventory at the process of Fit Blind as the Blind started to place on was recorded in 47% of valves removal process.

Table 6-6: The Measurement of Stage 1

Classification	Maintenance Hours	Processing time variation for each type of activity	Difference between CT and PT for each type of activity
CT	20.65		
PC	11.85		
VA – tool activities	6.5	0.8	4.2
NVABN	3.85	0.7	4.6
Waste in PT in total		1.5	
Difference between CT and PT in total			8.8

- Current state analysis for Stage 2

Stage 2 is the offsite refurbishment of the removed valves. There are 12 processes in stage 2, the classification of VA and NVA but necessary for both maintenance and administrative activities were elaborated in Table 6-7. There were five main tool activities and seven NVA but necessary activities were recorded in current process, two of the NVA but necessary are administrative activities were measured.

Table 6-7: The Classification of VA and NVA but Necessary Activities in Stage 2

Category	Level 1	Level 2	
		Maintenance activities	Administrative activities
VA	Main tool activities	• Strip valve – work front • Assess valve against scope – team leader • Prepare and rebuild valve – techs team • Pressure test/calibration – techs team • Offsite paint – paint vendor	• Delivery note issued • Delivery note completed
NVA but necessary	Supportive activities for critical resources	• Goods receival – operations • Return to goods out – warehouse coordinator • Packaging/preservation – tech team	• Communication between team leader and vendor coordinator • Communication between tech team and supply chain
	Critical quality inspection activities	• Verify valve - QA/QC QA/QC – engineers	• QA/QC sign on/off – vendor • QA/QC sign on/off – QA/QC staff from clients

As shown in Table 6-8, the total cycle time at Stage 2 was 25.9 hours and the processing time was 18.35 hours. 23 hours are categorised as VA, 2.9 hours are NVA but necessary. 5.195 hours process time variation (excess processing time) and 7.55 hours differences between cycle time and processing time were observed and need to be analysed. The PTV at this stage is higher than Stage 1 which indicates a big variations of the processing time at the offsite operation.

Table 6-8: The Measurement of Stage 2

Classification	Maintenance Hours	Processing time variation for each type of activity	Difference between CT and

			PT for each type of activity
CT	25.9		
PC	18.35		
VA – tool activities	23	4.3	7.4
NVABN	2.9	0.895	0.15
Waste in PT in total		5.195	
Difference between CT and PT in total			7.55

- Current state analysis for Stage 3

Stage 3 was related to the valve installation. There were 18 processes at this stage, the classification of VA and NVA but necessary for both maintenance and administrative activities were elaborated in Table 6-9. There are six main tool activities and eleven NVA but necessary activities were recorded in current process, five of the NVA but necessary are administrative activities were measured.

Table 6-9: The Classification of VA and NVA but Necessary Activities in Stage 3

Category	Level 1	Level 2	
		Maintenance activities	Administrative activities
VA	Main tool activities	• Remove blinds – mech/techs teams and operation team • Lift valve in and pin – mech Team and crane operator • Complete bolting and torque – mech team • Electrically reconnect & instrument air – INLEC • Stroke Valve – INLEC • Action punchlist items – all relative disciplines	• WPs sign off – team leader • Mech packs close out – supervisors • Inlec packs close out – supervisor

NVA but necessary	Supportive activities for tool operation	• Valve lifting: - Crane operator	• Communication between supervisor and crane operator, rigger and dogman
	Supportive activities for critical resources	• Logistics for equipment/tools transportation - mech/tech teams • Logistics for off load – truck driver • Logistics for onsite moving – truck driver • Receipt goods – supply chain	• Communication between mech/tech teams and material office/storeman • Communication between supervisor and mech/tech teams • Communication between schedule coordinator and truck driver
	Critical safety checking activities		• Communication between supervisor and truck drivers • Communication between supervisor and off-site supply chain
		• Complete vessel closure certificate – operation team	• Communication between operation team and HSE inspector
	Critical quality inspection activities	• Close out SAP workflow – QA/QC	• Communication between coordinator and inspector
		• Punchlist – commissioning team	• Testing sign on/off - supervisor • Commissioning record - inspector
	Permit authorisati on	• Permit sign on/off - operation team	• Permit arrangement - supervisor

			• Communication between operation team and permit manager

As shown in Table 6-10, the total cycle time at Stage 2 was 30.95 hours and the processing time was 18.95 hours. 6.44 hours were categorised as VA, 7.45 hours were NVA but necessary. 5.06 hours process time variation (excess processing time) and 12 hours differences between cycle time and processing time were observed and need to be analysed. The difference between cycle time and processing time at this stage was higher than Stage 1 and 2 which indicates a large amount of wasted time at the valve installation. Some of the serious issues have been visualised in the processes, for example, 30-40mins delay at the process of remove blinds to wait for operation attendances, etc.

Table 6-10: The Measurement of Stage 3

Classification	Maintenance Hours	Processing time variation for each type of activity	Difference between CT and PT for each type of activity
CT	30.95		
PC	18.95		
VA – tool activities	6.44	2.56	5.25
NVABN	7.45	2.5	6.75
Waste in PT in total		5.06	
Difference between CT and PT in total			12

6.3.3. Waste Analysis

Once the waste in the maintenance process was revealed in the current state map, it is useful to conduct a waste analysis to identify the root causes. The waste analysis was performed according to the method proposed. First, the reasons (root causes) leading to the waste in each activity in the value stream were identified. This action is guided by the cause and effect diagram. The root causes of variations in each activity were identified from the 6 categories. Table 6-11 lists the identified 18 individual causes that distributed among the 6 categories.

Table 6-11: Causes of Variation in Valve Replacement

Category	Causes of variation in maintenance execution	The type of waste	Causes of variation in administration	The type of waste
System	Challenge process: lack of prioritisation of valve isolations and painting	Unproductive work		
	Unplanned work: potential for issues regarding tooling for unplanned work at vendor	Unproductive work		
	Delay of previous work: unfinished previous work (rework, poor quality)	Overproduction	Inefficient off-site communication	Ineffective data management
	Criteria: criteria re-assessment of the painting of valve	Defects		
Environment	Severe weather	n/a		
Process	Interface conflict: other contractor interfaces prevent works	Waiting		
	Unavailable work front access	Waiting		
	Permit issued: error of the required permit	Waiting		
	Permit sign on: operation unavailability due to inefficient permit sign on	Waiting		
	Delay of QA/QC process	Waiting		

Category	Causes of variation in maintenance execution	The type of waste	Causes of variation in administration	The type of waste
	Late or unavailable inspector	Waiting		
Equipment and tools	Delay in crane availability prior to valve removal	Waiting		
	Conflict resource usage: delay of onsite shared resource due to high WIP	Waiting		
	Error of tools, equipment	Waiting		
People	Unavailable of required labour force	Waiting		
	Lack of skill/experience to perform the activity	Unproductive work		
Material and components	Delay of required material: incorrect material, potential delay or long searching time	Defect/unnecessary motion		
	Delay of logistics: logistics support delays for initial valve transportation	Waiting		

In order to determine the main causes that led to variation, the root causes of processing time variation were ranked based on the amount of variation they caused. Table 6-12 shows the top 10 causes in terms of processing time variation. Errors of tools was ranked as no.1 of the causes, 10% error rate of the tool, equipment staging was observed. It lead to 2.1 hours waste in the processes. Permit issue/isolation was the second main causes wasted 1.5 hours. Delay of required material was the third causes with 1.4 hours waste. The top 10 causes lead to processing time variation can be categorised to three groups: (1) the extended processing time due to the unavailability of the required resources to finish the tasks, such as labour (R8), material and components (R3), tools and equipment (R1, R7), and permit (R2); (2) processing time variation due to inefficient planning, include R4, R5 and R6; (3) environment issues of unavailable work front access (R9) and interface conflict (R10).

Table 6-12: Top 10 Causes of Processing Time Variation

Causes	Rank	Category	Hours
Error of tools, equipment: 10% error rate of the tool, equipment staging	1	Tools and equipment	2.1
Permit issue/isolation	2	Process	1.5
Delay of required material: incorrect material, potential delay or long searching time	3	Material and components	1.4
Challenge process: lack of prioritisation of valve isolations and painting	4	System	1.2
Delay due to administration work	5	System	1.0
Unplanned work: potential for issues regarding tooling for unplanned work at vendor	6	System	0.8
Delay in crane availability: delay in crane availability prior to valve removal	7	Tools and equipment	0.8
Lack of skill/experience to perform the activity	8	People	0.8
Unavailable work front access	9	Environment	0.6
Other contractor interface conflict prevented works	10	Environment	0.39

The root causes of starting time variation were also examined using a similar approach. As shown in Table 6-13, the top 10 causes of starting time variation were summarised based on the responses of experts in the focus group. The variation of starting time was mainly caused by (1) the completion of previous work (R1); (2) the preparation of prerequisite work, such as the availability of the logistics (R2), crane (R3), tools and equipment (R4), permits (R6), required labours (R7), and administration work (R9) to start the tasks; (3) inefficient planning (R5, R8); and (4) conflict work platform (R10).

It is interesting to note that 9 of top 10 causes of starting time variations overlap with the causes of processing time variation. The exploration of the "root causes" of start time variation can lead to the discussion of the reasons of processing time variation. Therefore, considering the consistency of the reasons identified in both causes of processing time variation and start time variation, the improvement in the future state would focus on reducing the top 10 causes identified in processing time variation.

Table 6-13: Top 10 Causes of Start Time Variation

Causes	Rank	Category	Hours
Delay of previous work	1	Process	3.85
Delay of the logistics to deliver required material	2	Material and components	3.15
Delay in crane availability: delay in crane availability to start the job	3	Tools and equipment	2.8
Delay of tools and equipment required	4	Tools and equipment	2.5
Excess transportation due to lack of prioritisation of valve isolations and painting	5	System	2
Permit issue/isolation	6	Process	1.8
Conflict labour resource to perform the activity	7	People	1.55
Unplanned work: potential for issues regarding tooling for unplanned work at vendor	8	System	1.35
Delay due to administration work	9	System	1.1
Conflict of work platform	10	Environment	0.95

6.3.4. Future State Improvement

The focus of FSM is to eliminate the root causes of wastes and to link the value stream in a smooth flow. The identified waste was estimated and validated by experts to propose an achievable improvement plan of the maintenance processes. The following priorities emerged out of the Impact/Effort Matrix (see Table 6-14). Waste elimination starts from the causes of variation with extremely high priority.

Table 6-14: The Priority of Causes Elimination

Priority	Causes
E	2, 4
H	5, 3, 7, 8
M	9, 6, 10
L	N/A

The wrong permit issued and lack of prioritisation of valve isolations and painting are the two causes have the extremely high priority. Delay due to the unavailability of material required, administration work, crane, and unskilled workers are the four causes have the high priority. Unplanned work, unavailable work front access, and interface conflict are the three causes have medium priority. The causes were listed independently while they occurred during maintenance process interdependently and simultaneously.

In response the findings of the prioritised causes of variation, three main lean improvements were proposed. The goals for maintenance execution process are to (1) improve workflow by removing obstacles between tasks of both operational and information flows; (2) increase flow reliability of operation, resource supply, and information: reduce the waste due to unfulfilled conditions to complete an activity; and (3) reduce flow fluctuation within distinct maintenance locations. Figure 6-5a, b, and c are the future state maps of the three stages.

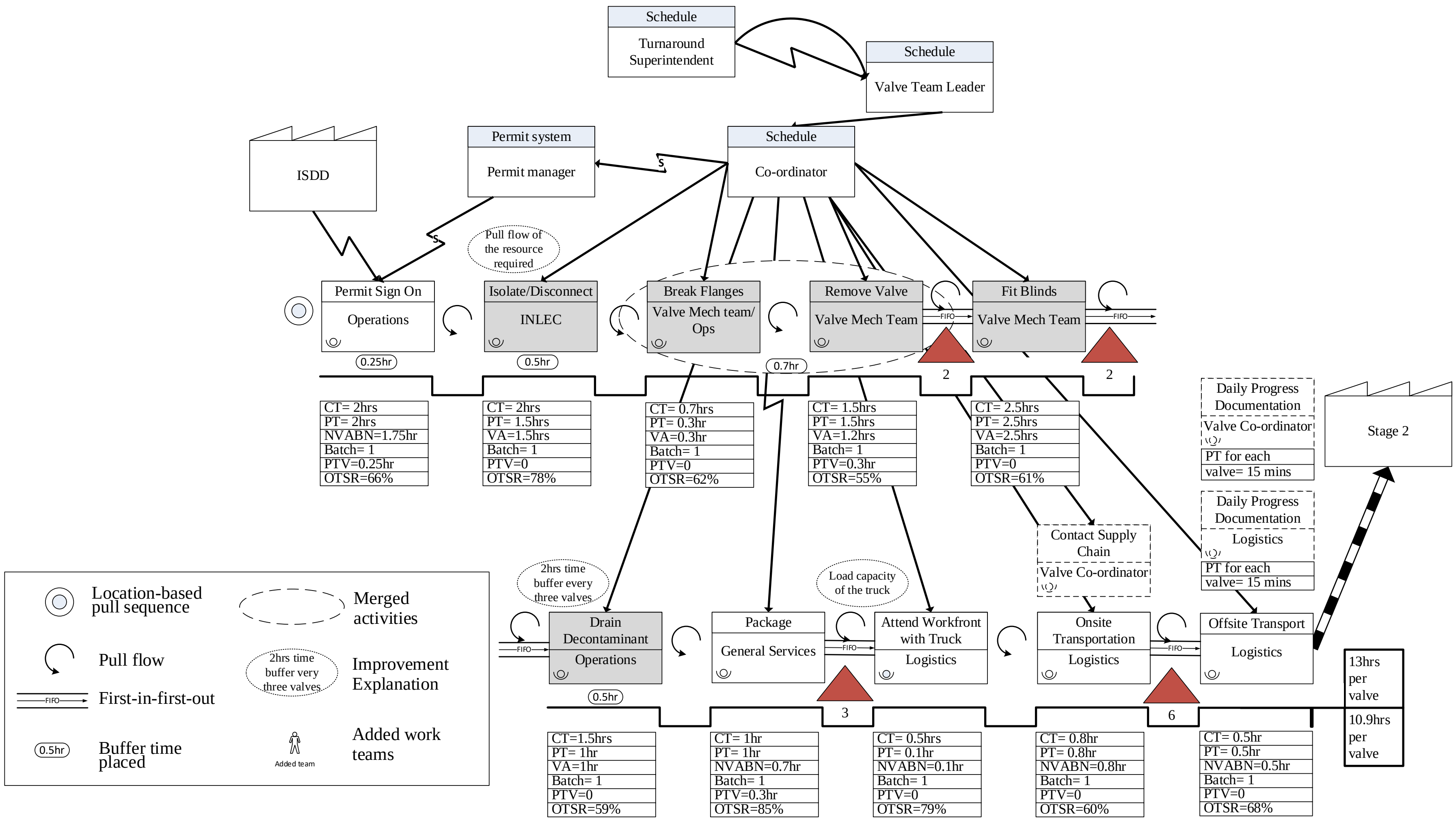

Figure 6-5a: Future State Map of Stage 1

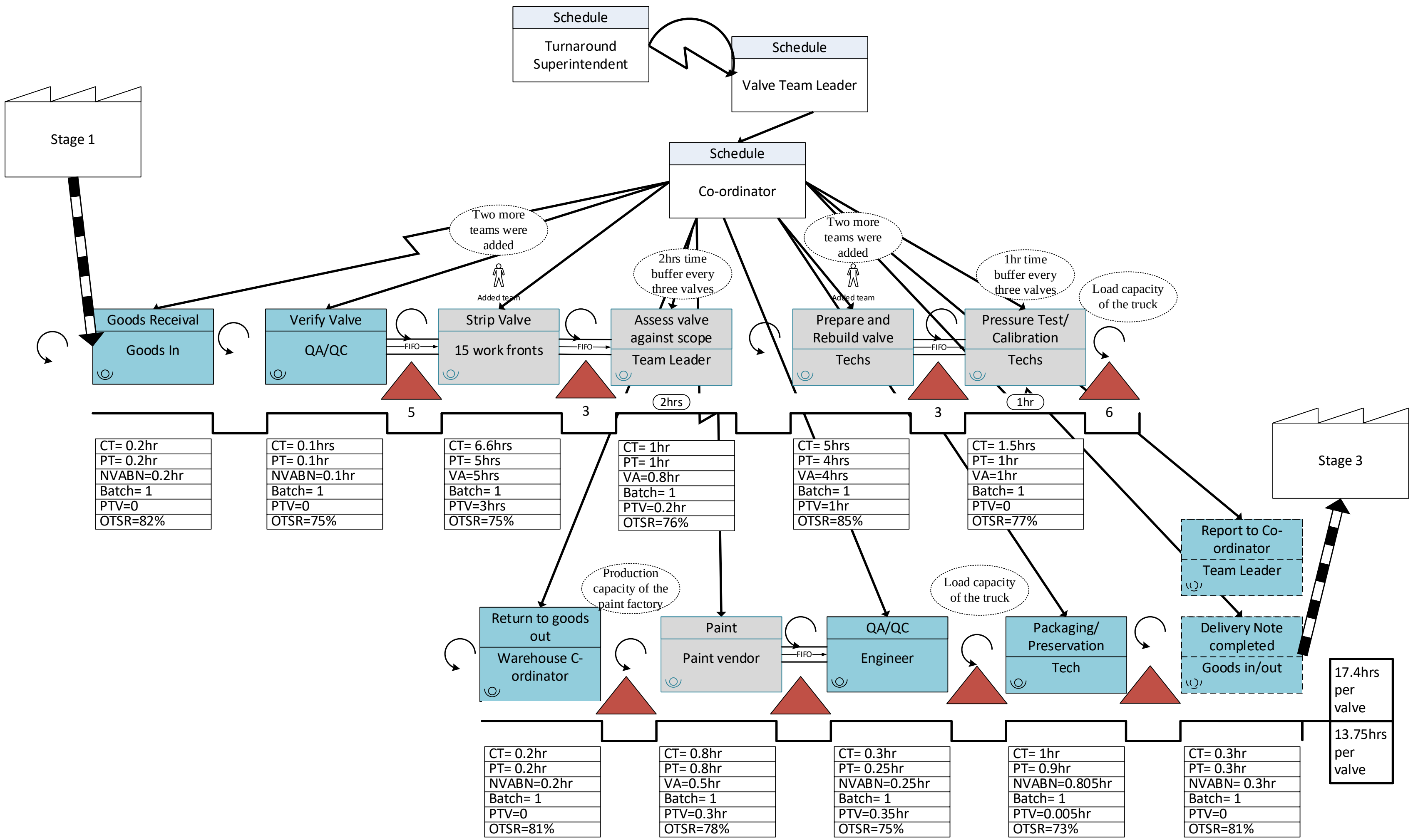

Figure 6-5b: Future State Map of Stage 2

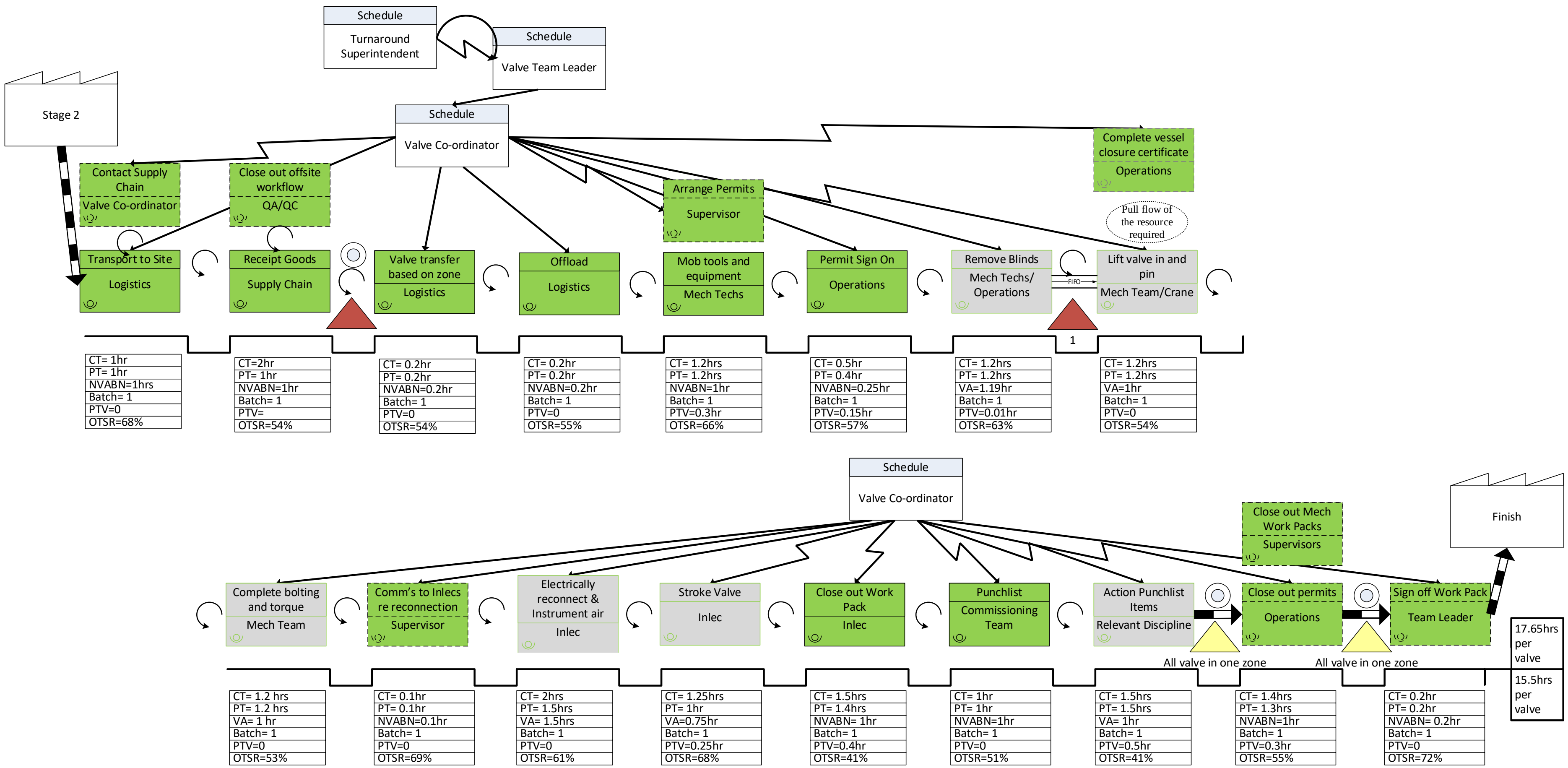

Figure 6-5c: Future State Map of Stage 3

Standardisation

The first improvement strategy focuses on identifying and removing redundant interfaces between activities and standardising procedures in work flows. The management in operation process aims to create a continuous flow by providing comprehensive resources and information to facilitate the efficient maintenance execution. The objective of process standardisation is to clarify and simplify the interfaces to reduce complexity for participants in workflows. The waste such as the variation caused by inefficient permit sign on could be essentially eliminated.

The process of interface standardisation is performed by reducing the inefficient and redundant management interfaces in communication procedures among participants and the documentation processed. The flowchart technique is used to map the program logic sequence of all the interface required. This technique gives a high level of detail of the flows to identify bottlenecks of the interface where the process can be improved. The complexity of activity is measured by multiplying the number of work teams by the number of interfaces in the process.

In this case, 15 managerial processes to provide the required resources and information to conduct an activity have been identified (as shown in Table 6-15). A process flowchart was drawn for each managerial process based on the information collected from both interview and document reviewed. The flowchart analysis follows the processes as below:

- Attaining an understanding of the steps of a managerial process;
- Identifying risks and interfaces in the managerial process;
- Understanding the individual’s view of the processes;
- Analysing inefficient interfaces;
- Validating by business leaders.

Table 6-15: Management Procedures Standardisation

Managerial processes	Output
• WP development • Schedule planning and design • Permit system • SAP WO/WP creation	• Summary of the management interfaces • Standardised management procedure

Managerial processes	Output
• Site manager’s work procedure • Communication and documentation among subcontractors • Communication and documentation among disciplines • Supply chain process • Quality check • QA/QC • Material procurement/receivable library • Tool and equipment • Progress record and tracking • Health & safety • Logistic support	

However, the results of process standardisation are not shown in this study as the information are confidential. The analysis of the flowchart of QA/QC management was shown as an example of standardisation improvement in this research. Figure 6-6 is the flowchart demonstrate the sequence of steps and document interfaces with respect to auditing operation standards and material delivery. It is observed that (1) the current QA/QC heavily reply on paper based records; (2) multiple handling of information handling and transportation; and (3) various information interfaces to perform auditing process. The potential risks include delay or information loss due to record creation, storage and transfer. Table 6-16 shows the 8 management platforms have been involved in these processes. The possible solutions were proposed after interface analysis, including: (1) create a new management platform that my incorporate all the functions and requirements to minimise multiple handling and transfer; (2) make the SAP work packages accordance with operation process; (3) consistent approaches to resourcing work job to make operation easier.

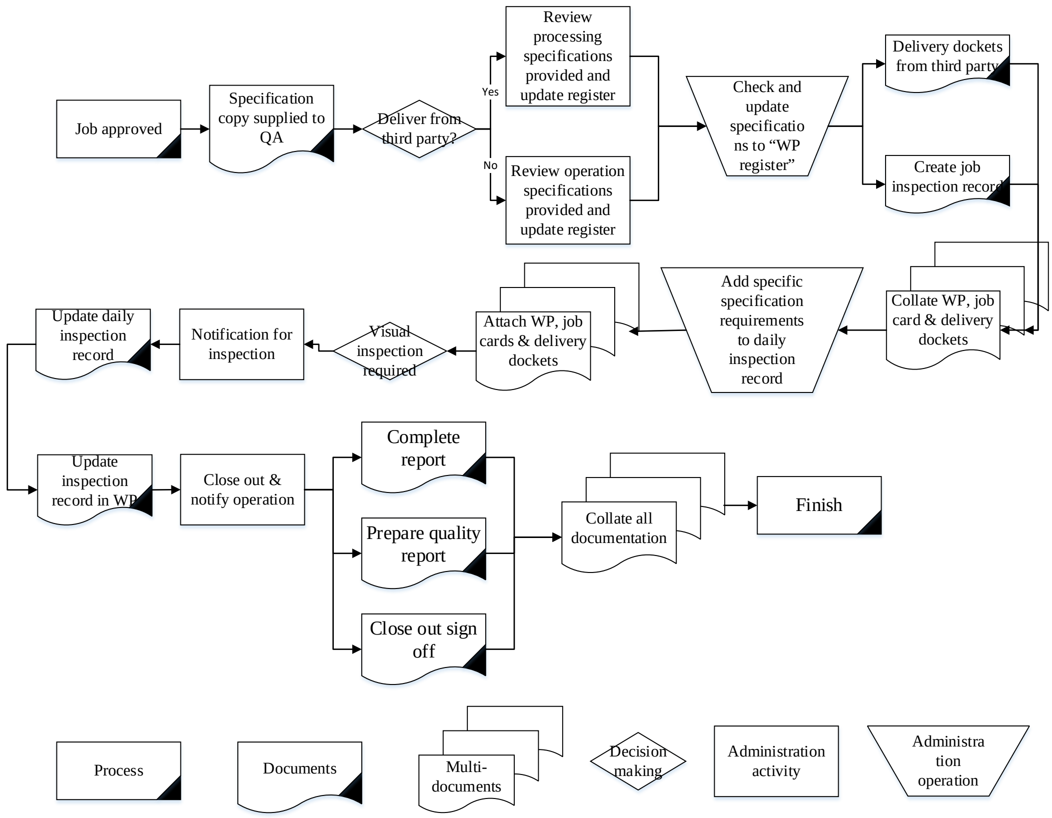

Figure 6-6: The Current Management Process of QA/QC

Table 6-16: The Management Platforms in QA/QC Processes

Management platforms	Fill type	Generation
Work package description	Digital	Superintendent
Operation specification	Digital	Operation manager
Delivery dockets	Digital	Logistic/warehouse
Job inspection record	Handwritten/digital	QA/QC
Daily inspection record	Digital	Operation manager
Work package inspection record	Digital	superintendent
Complete report	Handwritten/digital	operation manager/scheduler
Quality report	Handwritten/digital	QA/QC
Close out sign of	Digital	Operation manager

As shown in Figure 6-7, the management platforms were resorted according to the functions. The operations in work package were managed in an integrated SAP system and the records of QA/QC operation were integrated and managed by QA/QC staff. The interactions between teams/departments were minimised. The management platform in the process reduced to four from nine.

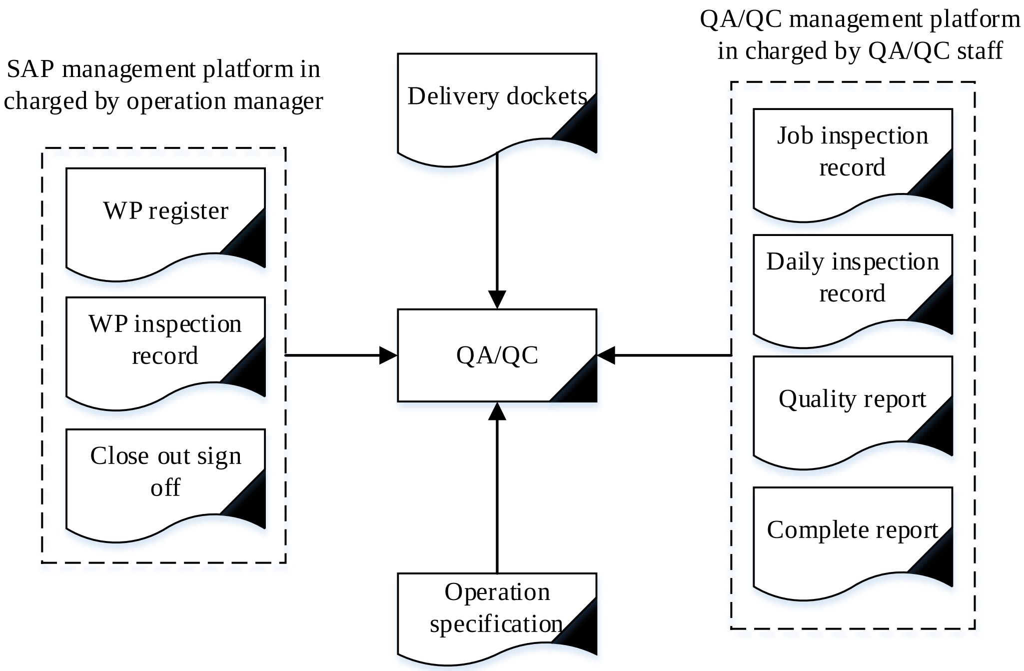

Figure 6-7: The Standardisation of QA/QC Processes

Location based operation levelling

The second improvement aims to reduce flow fluctuation of the maintenance operation within distinct locations. According to Russell's theory, the conventional schedule techniques is referred as activity-based for the management relies on the construction of a logical network of activities (Kenley and Seppänen 2006). While the waste, such as idle times of the sequential completion between activities, which caused by the operation rate fluctuation of the activities within different locations, can't be observed and solved in the linked network. The methodology of location-based management which proposed by Kenley and Seppänen (2006) is borrowed in this study to reduce such kind of waste. The focus of location-based scheduling is to track the continuity of the workflows of resources as well as the value stream of activities. The underlying philosophy is to flow resources for production processes through locations to reduce cycle time, as well as to use buffers to allow for variability.

In this research, this location-based flow management philosophy is combined and implemented with the concept of takt time to level the maintenance operation. Takt time planning in TAM project supposes to be the overall progress rate at which all the co-dependent flows in maintenance execution are ideally moved. However, takt time is a sort of customer-driven pull concept, it would be a problem to define the demand rate of workflow in the conventional push model of project management. The concept of production levelling proposed by Frandson, Berghede, and Tommelein (2013) in terms of the use of the takt time in push model is adapted. The identification of uniform operation rate for the TAM maintenance is guided by following processes:

(1) Division of the maintenance processes. The first step is to divide the maintenance processes into several stages according to the functionality. Takt time is measured respectively in stages. This step is added to minimise the impact of the varied pace of operation. In this case, takt time of the three stages is calculated respectively.

(2) Zone definition. The second step is to divide maintenance operations into zones. Each zone includes the components served on nearby facilities. In this case, the 100 valves are scattered at 6 different facilities and divided to 4 zones. The maintenance process is re-organised so that the valve replacement start from the valves at the same zone and the operations flow from one zone to another. Figure 6-8 shows the flow of operation considering both zones and stages.

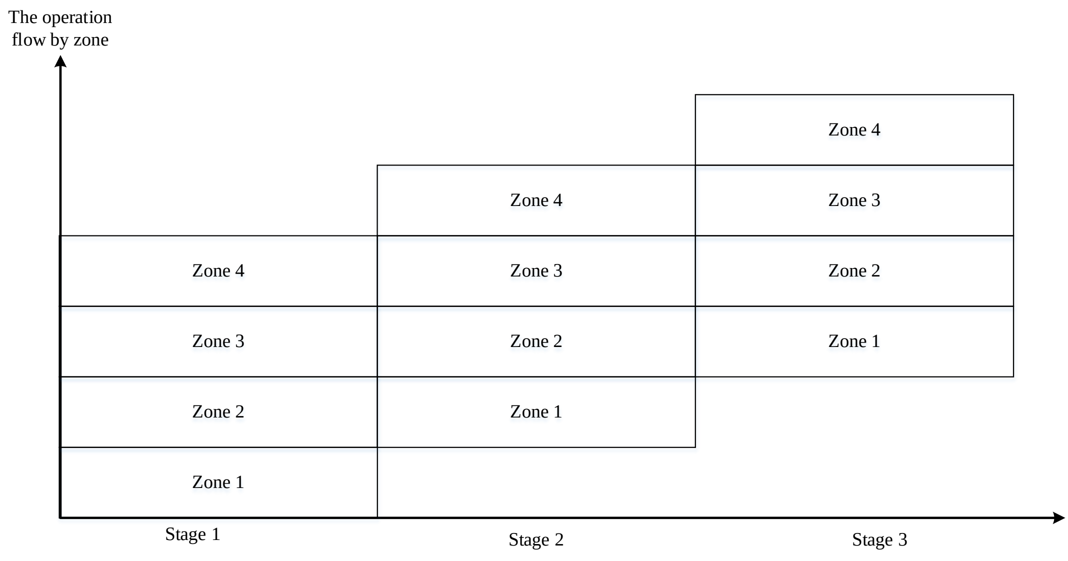

Figure 6-8: The Flow of Operation

(3) Workflow balancing. The third step is to refine the processing time of the maintenance executions. As shown in Figure 6-9, first, the processing time of the activities conducted for the valve replacement are measured. It is assumed that the same activities take the same processing time. Second, activity in the process with longest processing time is identified and adjusted by considering the feasibility to improve the

production capacity. This step is repeated until the maximum operation capacities to complete the activity is reached respectively. The adjustment strategies include increase the number of workers and restructure the activities to create a continuous flow. Third, the operational capacities in different activities are balanced. The actions include planning time buffers to accommodate the production or decreasing the number of workers to extend the processing time. Finally, a takt time for the production in the process is identified by referring to the processing time that could be followed by most activities. Those activities where there is a challenge to modify the capacities to get them match with the takt time, one of the solution is to use the controlled FIFO to manage WIP inventory (FIFO lane can be applied to decouple the consecutive activities with huge capacity variation); another solution is to add work team to reduce the impact of overlong production time. Time buffers are planned at the end of each finished process between zones to absorb the variations. Once applied, the takt time for stage 1 is 1.5 hours, 0.8 hours for stage 2, and 1.2 hours for stage 3.

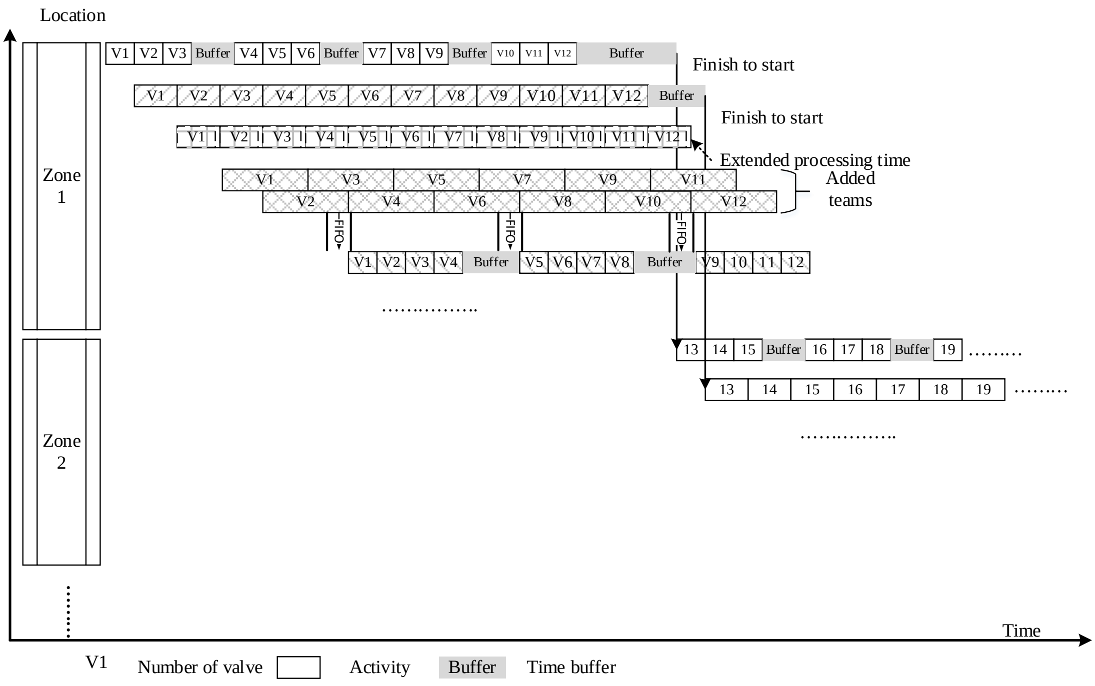

Figure 6-9: Workflow Balancing in the Same Stage

Dynamic pull flow

The third improvement is to propose a dynamic pull flow management to replace the fixed maintenance schedule. In the conventional method, the maintenance process is managed by using work break structure (WBS). The execution of maintenance activities pushes forward from the beginning to the end according to the planned sequence of WBS. It has been critiqued that this conventional project management technique puts pressure on producing faster to meet planned schedule rather than identifying the reasons for the inability to perform schedule (Ballard and Howell 1994). Therefore, this step aims to improve flow reliability by releasing the fully prepared activities.

The pull concept proposed in Last Planner System (LPS) was borrowed. LPS is a production planning and control system based on lean production principles, which helps increase planning reliability by measuring the performance of production (Ballard 2000). The fundamental idea of the proposed dynamic pull flow concept is to have the sequenced maintenance execution led by the availability of required work resources. The maturity of execution of the maintenance activities in the following shift will be assessed by the project manager. Ideally, only the maintenance activities with completely fulfilled execution conditions (e.g., permit issued, workers, material, equipment, and tools are available) can be introduced to the daily execution plan. The framework of total constraint management (TCM) is adapted to identify the constraints in three main categories (Wang *et al.* 2016): (1) planning constraints, (2) supply chain constraints, and (3) site constraints. Constraints such as lack of assembly specifications, delay of approval and unplanned job are related to planning constraints, which affect the start time of fabrication and site operation. Supply chain constraints include late delivery of newly purchased or refurbished components, project-specific instruments, and equipment. Without timely purchasing and delivering these resources to the site, detailed maintenance activities cannot be executed. Site constraints contain the shortage of workforce, lack of temporary structures, limited workspace, uncompleted preceding works, bad weather, lack of work permits, and safety issues. For each activity in the processes was evaluated to identify the possible constraints and measure the impact. For example, the constraints analysis of the process of strip valve in stage 2 was shown in Figure 6-10.

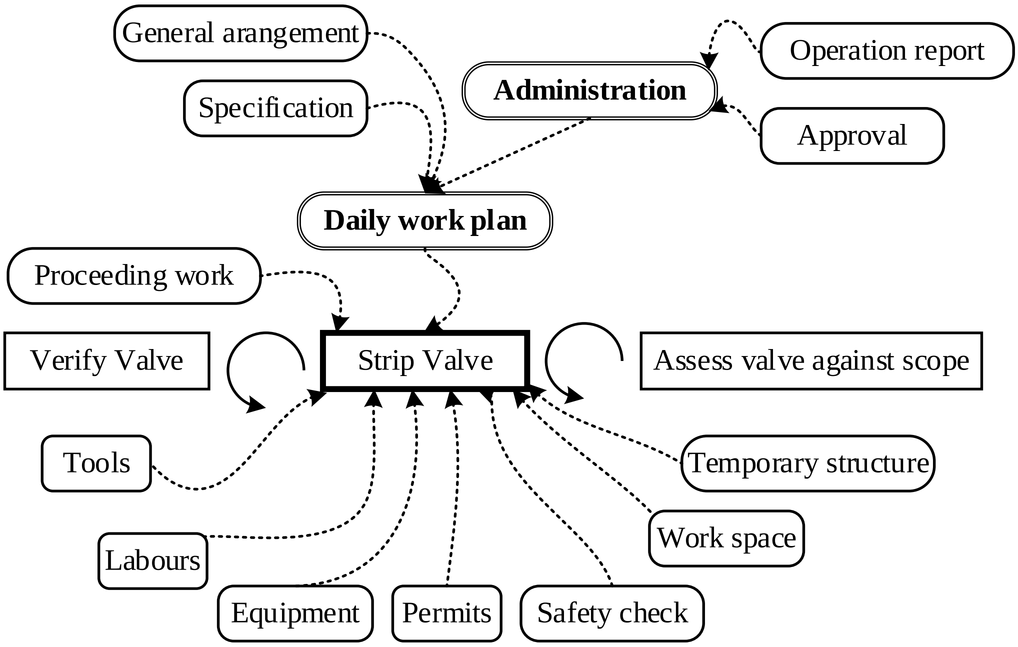

Figure 6-10: The Constraint Analysis

In real practice, some activities might be difficult to have 100% maturity because of the unavoidable variables. In this research, in order to cope with variations to improve the rate of "mature" activities to be introduced into the daily execution plan, the pull-based flow management is adopted with two enhancements:

- First is to manage the activities on the critical path. The release of "mature" activities is prioritised based on milestone completion. In other words, the activities are released to execution with prioritisation considering its impact on a specific milestone. Therefore, an activity even with less than 100% maturity could be introduced in the operation process.

- Second is to manage the activities on uncritical path activities, minimum necessary time buffers are assigned to absorb the variations in the process. The buffers should be carefully monitored to avoid its impact on critical path operation.

Process improvement measure

The maintenance process on the future stage map shows significant overall improvement. As shown in Table 6-17, the total amount of cycle time has 29.45 hours reduction. The total processing time decreases from 49.15 hours to 40.19 hours. The percentage of on-time starts increased from an average 35% to 65% and VA ratio increases from 49.32% to 64.54%. There is also a significant decrease in the total number of interfaces in the process from 127 to 38.

Table 6-17: Comparison of the Lean Metrics for Current State and Future State

criteria	Current state value	Future state value	Changes
Total amount of cycle time (h)	77.5	48.05	29.45
Total amount of processing time (h)	49.15	40.19	8.96
The average percentage of on time start (%)	35%	65%	30%
VA ratio (%)	49.32%	60.37%	11.05%
The number of interfaces	127	38	89

6.3.5. Action Plan

Action Plan is undertaken to investigate the effect of the improvements proposed in future state map before proceeding to explore implementation in a pilot project. In this research, the application of the proposed improvements was evaluated in two parts:

(1) the management procedure standardisation in this case study was conducted by the managerial operation. Although the implementation of the standardised work interfaces in practice is a long-term process, there are numerous expected benefits once the proposed standardisation are implemented. One of the main benefits is that all the participants in the maintenance process can access the relevant and correct information without unnecessary waiting and procedures to deal with.

(2) the evaluation of the pull flow system and location-based levelling were carried out by applying 4D BIM. The discussion in terms of 4D BIM application for assisting lean improvement application is elaborated in the next chapter.

6.4. Summary

The main contributions of the proposed Enhanced-VSM framework to the body of knowledge are threefold: (1) extending the VSM application beyond the manufacturing production management into a TAM project management process. In current practice, TAM project is treated as a collection of sub-campaigns using a conventional project management method. The conflict between predetermined schedule and unpredictable reality results in significant wastes in the system. This research focused on VSM, which has been indicated as one of the best tools for process improvement from a lean perspective. This paper explicated the major challenges and proposed an Enhanced-VSM to utilising VSM in a TAM setting. A critical value stream was identified; and (2) defining the activities of VA and NVA beyond the manufacturing setting in a more practical and structural way. Due to the different perspectives of value creation and evaluation, this paper proposed a classification system of the VA and NVA activities for the value and waste identification in the TAM processes. It is key to attain the lean application in a practical way by (3) proposing a VSM application in TAM execution process to improve workflow reliability and stability. It offers a structural way to choose the key value steam of a complex TAM campaign and to perform an optimised analysis of the selected value stream. Location-based levelling is used, in tandem with takt time redesign and pull planning rebuild, in order to control the variations and to provide a predictable and stable flow of work trades.

Chapter 7: 4D BIM Technique Application in Improving Action Plan Development and Implementation

7.1 Introduction

Chapter 7 investigates the capabilities of 4D BIM technique in improving the development and implementation of an Action Plan. The purpose of the Action Plan is to transform the current state VSM (i.e. low process efficiency) to the future state VSM (i.e. high process efficiency) developed in Section 6.3, Chapter 6. 4D BIM has been credited with improving construction planning and control procedures. The integration of 3D model with schedule information has enabled the effective detection of design and planning flaws in many construction projects. Due to the lack of research on using 4D BIM in TAM projects, this chapter will firstly introduce a novel framework of applying 4D BIM to improve TAM process efficiency by taking into account those improvement strategies (i.e. Standardisation, Dynamic pull flow, and Location-based levelling) proposed in Section 6.3.4, Chapter 6. Then, a real TAM project will be presented to demonstrate the effectiveness and efficiency of the proposed framework in transforming the current state VSM to the future state VSM. Finally, other benefits such as time and cost reduction, and safety improvement will be also calculated and explained.

7.2 Framework of Applying 4D BIM to Improve TAM Process Efficiency

This section describes a 4D BIM framework for improving TAM process efficiency (as shown in Figure 7.1). In the left part, a typical TAM project structure is developed which consists of six levels of details based on the functional logic (Bevilacqua *et al.* 2009; Bevilacqua *et al.* 2005). The first level is defined based on a TAM project unit, which explains the project scope, cost, planning, governance, key performance indicators, health, safety, environment and quality, and emergency response. For a major shutdown, a TAM project will contain jobs conducted in two or more independent trains. Therefore, a major TAM campaign is always divided into several sub-campaigns. Given a train-related sub-campaign, the third level classifies the jobs into a number of sub-sub-campaigns according to the plant unit, such as Compressor or Turbine. The fourth level further divides the related jobs within a sub-sub-campaign into different work orders according to the system unit, such as Piping, Mechanical, and electrical systems. The last two levels detail the work order into batch and activity units respectively. For instance, for a given work order of a spool removal, there are a number of elbows need to be uninstalled, in addition, detailed process for uninstalling a specific elbow also needs to be explained.

According to the TAM project structure, four levels of the 4D BIM simulation are developed including Plant, System, Batch, and Activity level (as shown in the right side of Figure 7.1). For a given level, the 4D BIM simulation is developed based on the corresponding level-of-detail 3D model and schedule. Each of them is explained in detail in the following sub-sections.

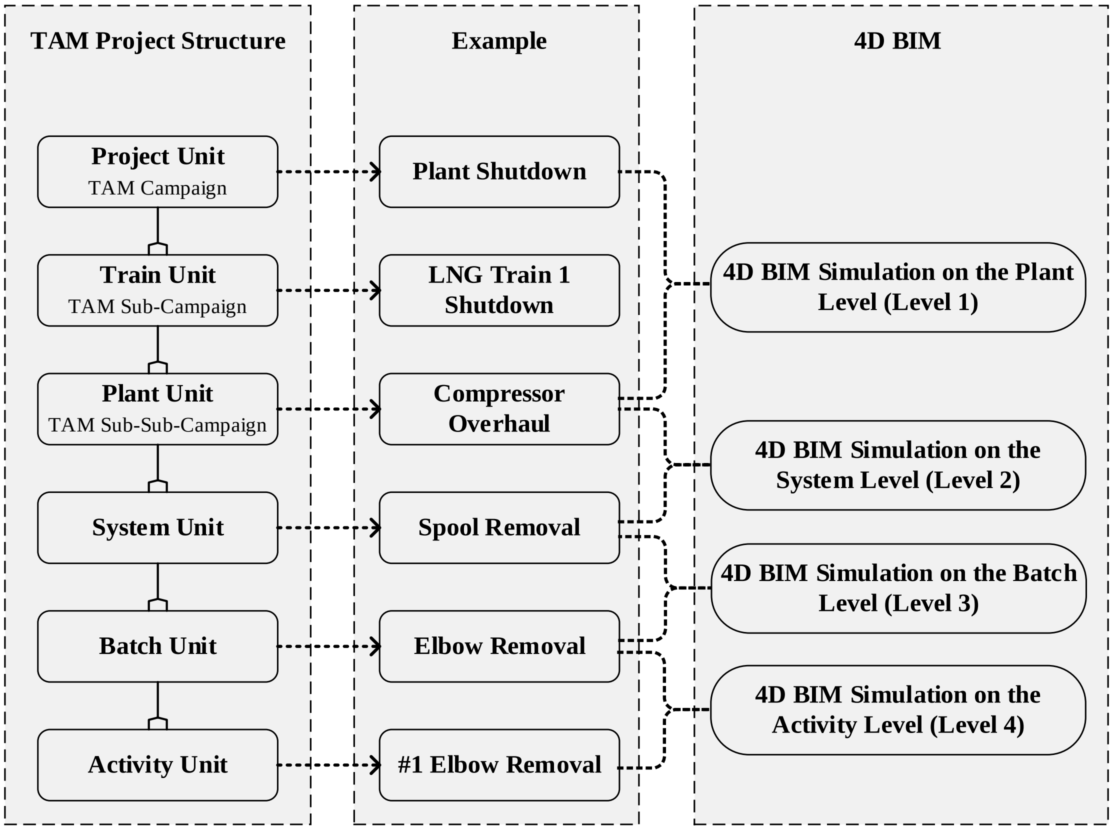

Figure 7.1: Framework of Applying 4D BIM to Improve TAM Process Efficiency

7.2.1 4D BIM Simulation on the Plant Level

The main objective of this level of 4D BIM simulation is to effectively engage core teams (i.e. Operations, maintenance & Integrity, and Turnaround Lead) to review the project scope. If the scope does not align with the initial plan, additional works, such as revising plans, need to be conducted before proceeding to the next stage. Therefore, the reviewing process is very critical to the turnaround success.

4D BIM modelling and simulation on this level is developed based on the 3D Plant Model and TAM milestone plan. In order to accelerate the agreement establishment among plant operation, maintenance, and turnaround teams, the 3D Plant Model should have all the main 3D objects (i.e. Compressor, Turbine, or Heat Exchanger) that defined within the project scope, and their functional location information. In addition, a general plant site model including site layout information should be also incorporated into the 3D Plant Model. The

TAM milestone plan should lay out the key checkpoints and delivery dates for the planning cycle and form the basis for forecasting planning resources.

The plant-level 4D BIM simulation should be developed ten to twelve months before starting the field execution. For small turnaround projects with no major material lead times, the completion data of this simulation can be 6-8 months before actual starting.

7.2.2 4D BIM Simulation on the System Level

The main objective of this level of 4D BIM simulation is to engage teams of Planning, Work Pack Development, Engineering, and Procurement to: (1) communicate and review terms of reference, discuss initial risks, functional requirements, likely resources and establish delivery strategy; and (2) review initial scope against turnaround acceptance criterial, prioritise tasks and establish initial work list.

4D BIM modelling and simulation on this level is developed based on the 3D System Model and TAM work development plan. In order to efficiently review and confirm initial work list and initial preparations plan, the 3D System Model should include: (1) all the connected components (i.e. Spools and steel structures) of the instruments that plan to be replaced; and (2) major construction equipment, such as mobile cranes, that plan to be used to perform lifting tasks. The TAM work development plan should include: (1) an integrated plan (schedule, equipment and resources); (2) preliminary critical path schedule; (3) updated preliminary work list; and (4) critical lift plans.

The system-level 4D BIM simulation should be completed six to eight months prior to the shutdown of the plant or equipment.

7.2.3 4D BIM Simulation on the Batch Level

The main objective of this level of 4D BIM simulation is to engage external contractors and/or out-of-plant personnel to evaluate the critical path, and come up with alternative execution methods to shorten the project duration. Reviews of maintainability, reliability, and constructability are the main focus at this stage.

4D BIM modelling and simulation on this level is developed based on the 3D Batch Model and TAM detailed plan. In order to efficiently finalise the work list, the 3D Batch Model should include: (1) supported structures such as steel platforms and scaffolds; and (2) safety signs and tags such as frame signs, swing stand signs, and barricading. The TAM detail plan should include critical and sub-critical activities, lifting plans, mobile equipment requirements, detailed shop loading plans, and what-if scenarios.

The batch-level 4D BIM simulation should be completed three to five months prior to the turnaround.

7.2.4 4D BIM Simulation on the Activity Level

The main objective of this level of 4D BIM simulation is to ensure that all parties understand the work to be done and the sequence and details of the shutting-down process together with preparation for entry.

4D BIM modelling and simulation on this level is developed based on the 3D Activity Model and TAM execution plan. In order to efficiently (1) train operations, maintenance, and contractor personnel and (2) review environmental and safety requirements, the 3D Activity Model should include: (1) temporary facilities such as temporary offices, stores, tool houses; (2) functional equipment such as lighting tower, gas detector, and hydrostatic test unit; and (3) virtual avatar. The TAM execution plan should include: (1) shutdown and unit clean out sequences, (2) start-up plan; and (3) detailed execution sequences.

The activity-level 4D BIM simulation should be completed two weeks to two months prior to the turnaround.

7.2.5 Comparison of the Four 3D Models

The four 3D models (i.e. 3D Plant Model, 3D System Model, 3D Batch Model, and 3D Activity Model) are used as a basis to develop the four levels of 4D BIM simulation, respectively. Table 7-1 summarises the level of detail of the four 3D models. The level of detail increases as the project proceeds.

In the 3D Plant Model, only major plant instruments that plan to be replaced are required to be modelled, such as Compressor, Vessel, Pump, and Tank. The 3D System Model is developed based on the 3D Plant Model. Detailed plant components around the major instruments, such as pipe spools, valves, and steel structures, are modelled at this time. In addition, major construction equipment (i.e. Crane) is also modelled to help TAM teams to evaluate the critical lift plans. The 3D Batch Model is developed on the basis of the 3D System Model, and contains another two 3D categories: temporary structures (e.g. scaffolds and mobile platforms) and safety signs and tags (e.g. barricading and frame sign). The 3D Activity Model is the most detailed one and contains all the four categories. Compared with the 3D Batch Model, more construction equipment such as lighting tower and hydrostatic test unit are added. Temporary offices, stores and tool houses are also modelled to help site workers to understand the site logistics. In order to assure personnel are capable of operating and maintaining any new equipment or facilities that are to be installed, different types of virtual avatars are created and placed into the 3D Activity Model.

Table 7-1: Comparison of the Four 3D Models

Categories	Components	3D Plant Model	3D System Model	3D Batch Model	3D Activity
Plant Component	Pipe		√	√	√
	Valve		√	√	√
	Pump	√	√	√	√
	Compressor	√	√	√	√
	Steel Structure		√	√	√
	Vessel	√	√	√	√
	Tank	√	√	√	√
Construction Equipment	Crane		√	√	√
	Gantry		√	√	√
	Gas Detector				√
	Lighting Tower				√
	Generator				√
	Hydrostatic Test Unit				√
Temporary Structure and Facility	Scaffold			√	√
	Mobile Platform			√	√
	Temporary Office				√
	Temporary Store				√
	Temporary Tool				√
Safety Signs and Tags	Frame Sign			√	√
	Swing stand Sign			√	√
	Barricading			√	√
Personnel	Virtual Avatar				√

7.3 Case Study

The case study was conducted based on a major plant turnaround project that consists of LNG Train 5 and Fractionation Train 1. The key activities involved in this turnaround include: (1) Turbine major inspection; (2) Statutory vessel inspections; (3) Compressor blade carrier change-out; (4) Bearing and seal inspections; (5) Tray modifications; (6) Molecular sieve bed change-out; (7) Mercury guard bed change-out; and (8) Valve overhauls, upgrades and replacements.

7.3.1 3D Model Development

The selected gas plant was built more than 30 years ago. There is a lack of a 3D model that can be used to create a 4D simulation. Fortunately, the laser scanning technology is becoming mature enough, and is affordable for current industry. There are lots of automated methods that have been developed for transforming point cloud data into 3D model (Tang *et al*. 2010). However, in this case study, the 3D model was created manually by engineers in order to assure the modelling accuracy. The underlying reasons are twofold: (1) Most of the existing algorithms developed for automatically transforming point cloud data into 3D model, are focused on building industry. When applying them in gas plant domain, the average accuracy of the transforming process is not acceptable. (2) The scope of this TAM project is small, only covering the Compressor-related area, thus both time and cost spent for creating the 3D model are affordable. Figure 7-2 shows the point cloud data, and Figure 7-3 shows the converted 3D model.

Figure 7-2: 3D Point Cloud Model

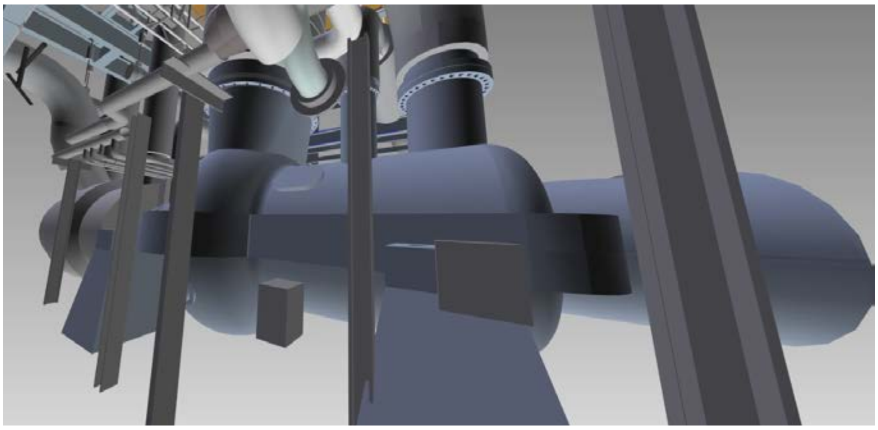

Figure 7-3: Converted 3D Model

7.3.2 4D BIM Simulation Implementation

In this case study, the four levels of 4D BIM simulation defined in Section 7.2 were developed as the project progresses. The proposed three lean improvement strategies (i.e. Location-based operation levelling, Dynamic pull flow, and Standardisation) described in Section 6.3.4, Chapter 6, had been implemented within the 4D BIM simulation. Specifically, the improvement strategy of location-based operation levelling was used to guide the task sequence planning and optimisation at the System level of 4D BIM simulation. The improvement strategy of dynamic pull flow was utilised to check the execution conditions of each activity at the Batch level of 4D BIM simulation, such as required permits, resource availability (i.e. material, equipment, and labour), and information availability (i.e. engineering, safety, and procurement), to assure construction site work flow. The improvement strategy of standardisation was utilised to improve site worker's productivity at the Activity level of 4D BIM simulation, which included process standardisation and interface standardisation. The details of the three types of lean improvement are presented in the following three Sections, respectively.

The aim of the 4D BIM simulation on the plant level is to help decision-makers to efficiently gain a better understanding of project scope and critical works. Therefore, none of the three lean improvement strategies was implemented at this level. Figure 7-4 shows the 4D BIM simulation on the plant level which visualises the major activities defined within the project scope.

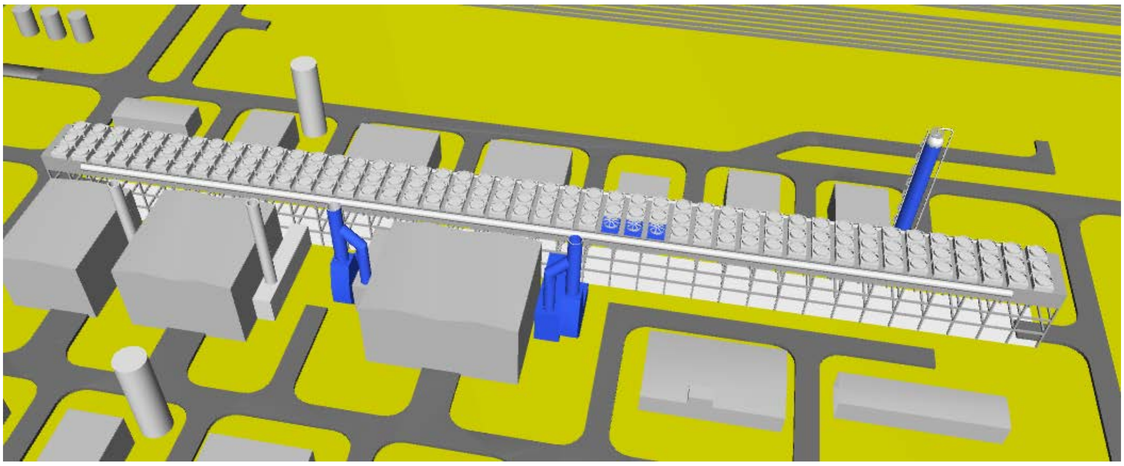

Figure 7-4: Screenshot of the 4D BIM Simulation on the Plant Level

The simulation was created by the TAM core team and presented to the project steering committee for guidance. Through the simulation, the steering committee had gained a better understanding of

(1) The thirteen major maintenance happened in LNG train 5, such as: gas turbine overhaul of *5KT1410* and *5KT1430*, process compressor overhaul of *5K1410*, *5K1420*, *5K1430* and *5K1450*, statutory inspections of 43 vessels, and *5C1410* tray modifications; and

(2) The nine major maintenance happened in LNG train 4 and Frac-3, such as: thirty control valve installations, three exchanger installation, product exchange of 4C2501, and compressor overhaul of *4K4401* and *4K4403*.

In addition, one critical workscope and three sub-critical workscopes were also determined in terms of their durations and dependences. The *5K1410* compressor overhaul was the critical one and it would take 20 days to complete. The sub-critical workscopes includes: *5KT1430* turbine overhaul (24 days), *5KT1430* turbine overhaul (25.5 days), and *5C1410* internal tray modification (13 days).

7.3.3 Lean Improvement Strategy 1: Location-based Operation Levelling

This strategy was applied at the System level of 4D BIM simulation (as shown in Figure 7-5). The simulation created for this case not only visualised the sequence of the main activities, but also detected the potential constructability issues of the lifting and access plans created by the TAM execution team.

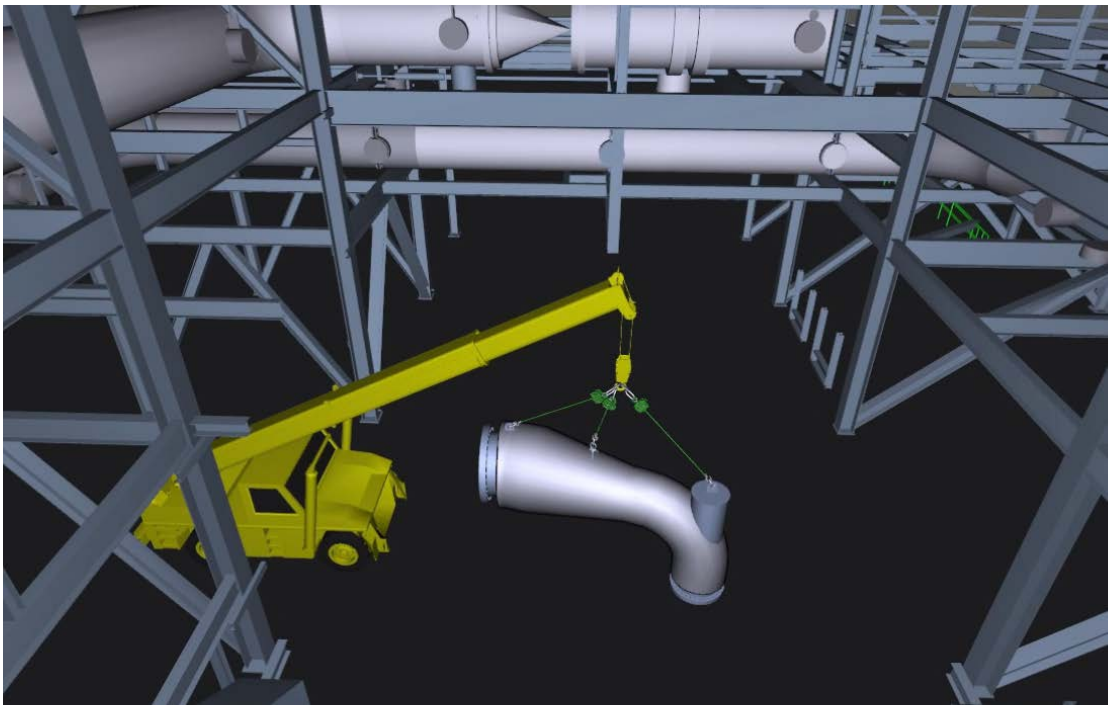

Figure 7-5: Screenshot of the 4D BIM Simulation on the System Level

LNG Train 5 was selected as an example to demonstrate how to use the improvement strategy 1 (i.e. location-based operation levelling) to eliminate crane operation conflicts and improve crane utilisation rate. The original lifting plan contained six mobile cranes. The working location and lifting capacity of each crane are shown in Figure 7-6a. According to the simulation results, seventeen major conflicts were identified between the planned construction sequence and the original lifting plan. For instance, Crane 2 was occupied by two main activities simultaneously during 9:30-10:18 on the 11th September 2015, and Crane 4 was occupied by two main activities simultaneously during 6:45-7:51 on the 18th September 2015. If these conflicts were not solved successfully before field execution, there would be fifty hours schedule delay and more than two hundred man-hours waste. These numbers were estimated by the TAM core team.

In order to solve the seventeen lifting conflicts, the TAM core team went through these conflicts one by one, and found that fourteen of them were related to the Crane 2 and 3. Therefore, they decided to add another crane located between Crane 2 and 3 to share the lifting load. The other three lifting conflicts were related to the Crane 4. Instead of adding a new crane, the TAM core team decided to enlarge the lifting capacity of Crane 5 from 20 tonnage to 50 tonnage so that it can share the lifting load of Crane 4. In addition, the working locations of Crane 4 and 5 were also adjusted to assure the lifting efficiency. Figure 7-6b illustrates the revised lifting plan for LNG Train 5.

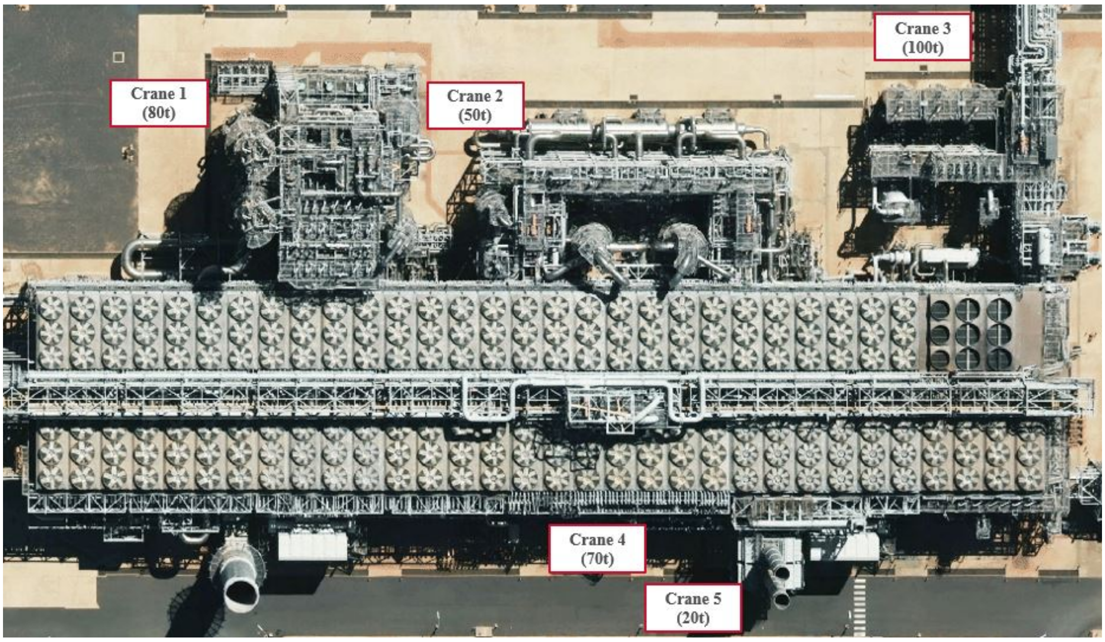

Figure 7-6a: The Original Lifting Plan for LNG Train 5

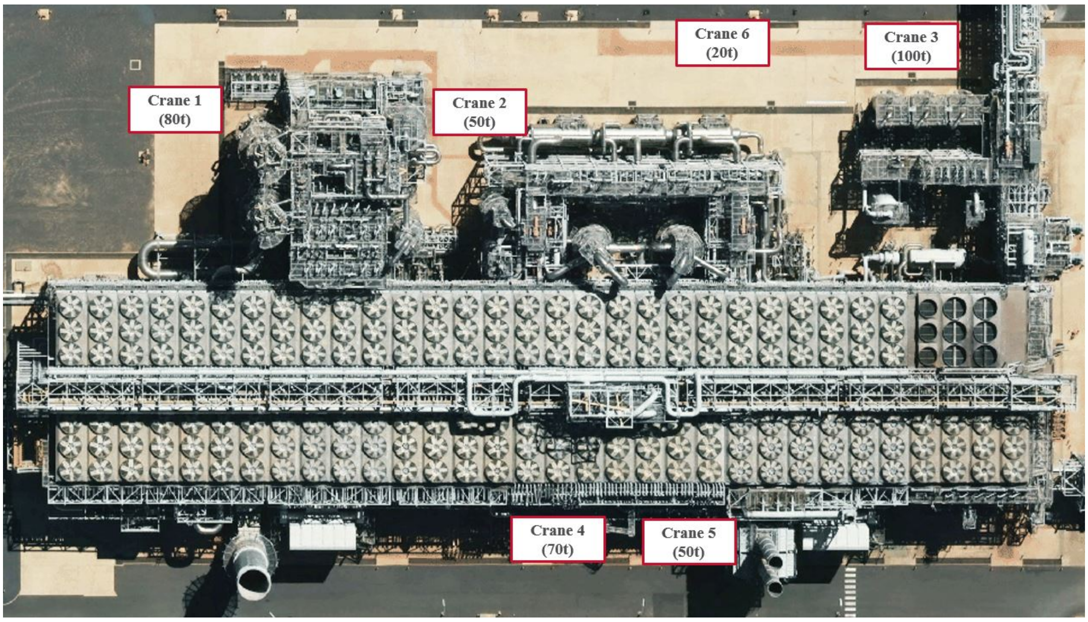

Figure 7-6b: The Revised Lifting Plan for LNG Train 5

7.3.4 Lean Improvement Strategy 2: Dynamic Pull Flow

This strategy was applied at the Batch level of 4D BIM simulation (as shown in Figure 7-7). The simulation at this level was developed by the TAM execution team, which visualised the sequence of all the activities involved including temporary jobs such as scaffold erection and dismantling. The core of the dynamic pull flow strategy was to check the execution conditions of each activity, such as predecessor work, temporal/spatial limitations, required permits, resource availability (i.e. material, equipment, and labour), and information availability (i.e. engineering, safety, and procurement). In order to assure all the conditions were identified and successfully solved, operations and maintenance teams were invited to join at this stage. A cloud BIM platform (as shown in Figure 7-8) was also developed to allow people from other shutdown projects but has similar working experience to easily access this simulation and comment their ideas remotely.

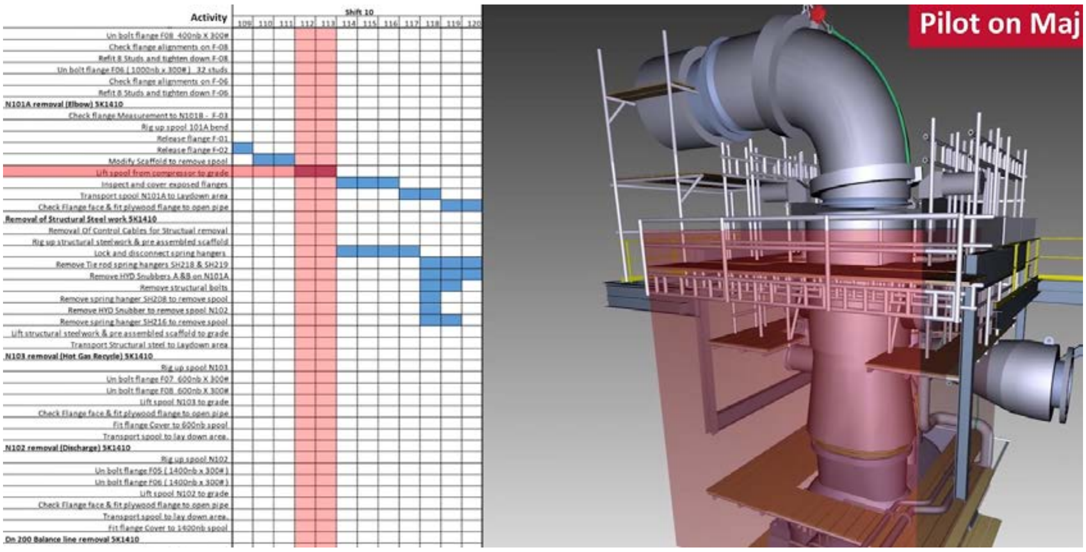

Figure 7-7: Screenshot of 4D BIM Simulation on the Batch Level

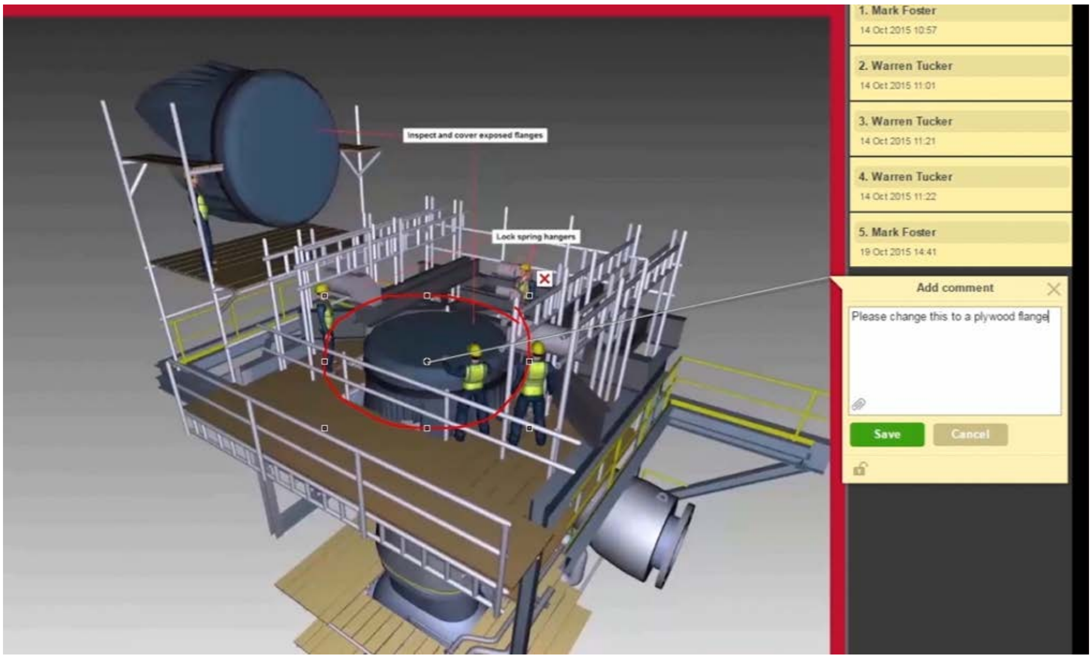

Figure 7-8: A Cloud BIM Collaboration Platform for Constructability Review

Figure 7-9 summarises the issues identified at this stage. A total of 104 issues were found by the TAM internal and external teams. These issues were further classified into eight categories, i.e. issues of Crane, Equipment & tools, Safety, Material, Work space, Permit, Activity Sequence, and Work front access. Incorrect activity sequence was the top one issue which accounted for 27% of the total issues. For instance, “This handrail is only installed once the steelwork has been removed”, “The scaffold should be modified first before removing the spool N101A”, “Remove spring hanger SH216 first before removing the spool”. Incorrect permit was the second most serious issues which accounted for 22%. TAM work requires extensive permits for every shift to ensure each work is performed safely. The plant engineering and operation teams contributed significantly on identifying these permit issues. For instance, they found that six activities were lack of appropriate permits, and another seventeen permits were incomplete and needed further development. Sixteen safety issues (i.e. 15%) and thirteen crane operation issues (i.e. 13%) were also detected through the Cloud BIM Collaboration Platform. The other three types of issues are work space (10%), work front access (9%), and equipment & tools (4%), respectively.

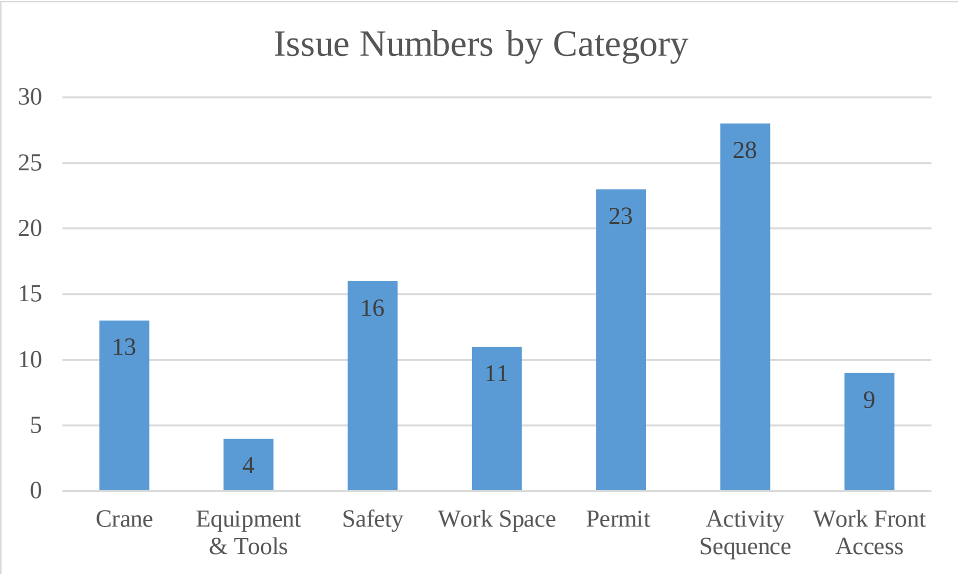

Figure 7-9: Issue Numbers by Category

7.3.5 Lean Improvement Strategy 3: Standardisation

This strategy was applied at the Activity level of 4D BIM simulation (as shown in Figure 7-10a). The simulation at this level contained TAM site work crews. Locations and travelling paths of work crews were shown during the simulation, especially during those working periods that contain massive concurrent activities. Rigging plans were also visualised including shackles, turnbuckles, and slings being used.

Two types of standardisation were implemented to improve construction workers' productivity which included process standardisation and interface standardisation. The former one was focused on clarifying and simplifying processes to reduce job complexity for site workers. The latter one was focused on reducing the inefficient and redundant management interfaces to improve field communication among different work teams. Visual standard work packages for each individual activity were created to guide the field execution (as shown in Figure 7-10b). In addition, these work packages were dynamic and could provide real-time status of the execution conditions. For instance, site workers could check the resource availability of a specific activity. If the required resource was not satisfied, the site workers could quickly find the responsible person who in charge of the resource delivery, which could significantly improve field communication.

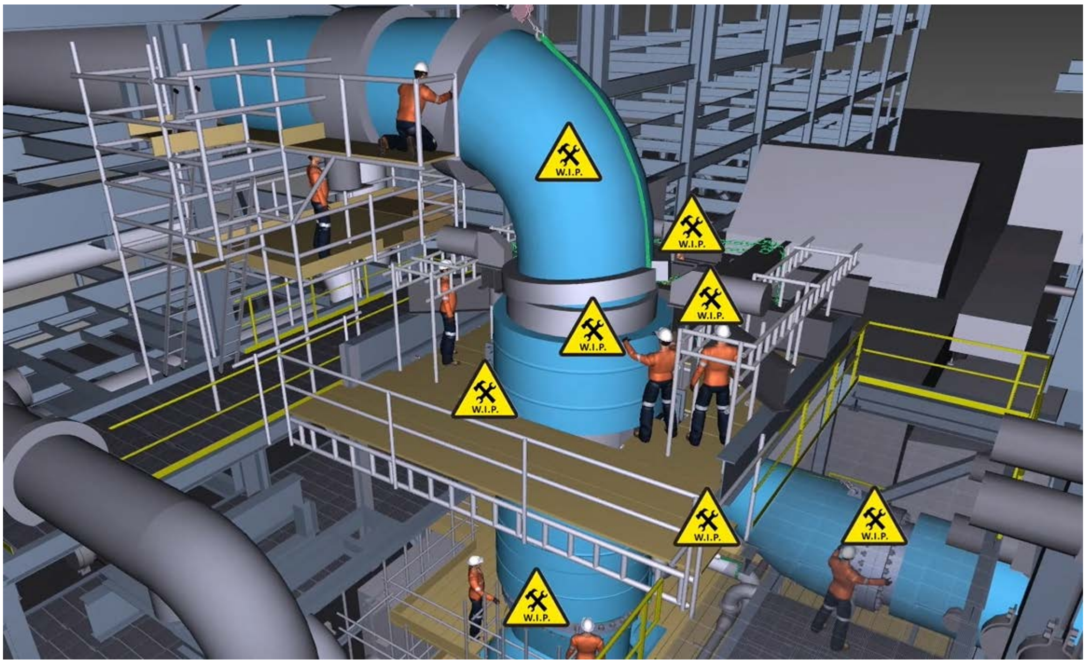

Figure 7-10a: Screenshot of the 4D BIM Simulation on the Activity Level

Figure 7-10b: Visual Standard Work Packages

7.4 Results and Discussions

In order to measure the BIM benefits, the case investigated in Chapter 6 was selected as a benchmark. As shown in Table 7-2, the distribution of value and waste were quantified after 4D BIM implementation and compared to current and future performance. Time and cost reduction and safety improvement were also measured by comparing the two projects' final reports. Detailed results are elaborated as follows.

7.4.1 Analysis of Value-adding and Non-Value-adding Activities

In order to measure the effectiveness and efficiency of the 4D BIM technique, the case investigated in Chapter 6 was selected as a benchmark. The valve replacement process within this TAM project was selected and quantified with the same Criteria defined in Section 6.3, Chapter 6. Table 7-2 illustrates the calculation results. Significant improvement had been achieved when comparing the "Current state value" with "Achieved state value". For instance, the total amount of cycle time had been reduced from 77.5 hours to 50.25 hours. It also should be noticed that the Achieved state value is very close to the Future state value, which means: (1) the Action Plan (i.e. the TAM project plan) generated from 4D BIM technique is effective; (2) the Action Plan has been implemented accurately in the field. The "Transformation rate" indicates how many percentage of the future state has been achieved. The greater the "Transformation rate" is, the more effective the Action Plan is. The average transformation rate in terms of the five criteria (i.e. Total amount of cycle time, Total amount of processing time, The average percentage of on time start, VA ratio, and The number of interfaces) is 85%.

Table 7-2: The Comparison of the Value in Current State, Future State and Achieved State

Criteria	Current state value (a)	Future state value (ideal value) (b)	Achieved state value by 4D BIM implementation (c)	Transformation rate ((a-c)/ (a-b)*100%)
Total amount of cycle time (h)	77.5	48.05	50.25	93%
Total amount of processing time (h)	49.15	40.19	42.55	74%
The average percentage of on time start (%)	35%	65%	63%	93%
VA ratio (%)	49.32%	60.37%	57.8%	77%
The number of interfaces	127	38	47	90%

7.4.2 Time and Cost Reduction

A quantitative analysis of the time and cost reduction is difficult because it should predict what would happen if the issues that detected by 4D BIM simulation are not resolved (Kim, *et al.* 2017). Instead of directly calculating each issue effect, a previous equivalent TAM project that conducted two years ago was selected as a benchmark to measure the time and cost savings. The raw execution data of the selected case were extracted from the Document Retrieval Integrated Management System (DRIMS) (i.e. a type of corporate document management system) and SAP (i.e. an enterprise resource planning system).

Figure 7-11 illustrates the maintenance duration reduction. The left column with red colour indicates the actual duration of the valve replacement, i.e. 14 days. The planning of the current TAM project started from the previous one, and after the first two levels of 4D BIM simulation (i.e. Plant level and System level), the initial expected duration was adjusted to 13.5 days. Before the field execution, the TAM team set the project target duration to 12 days based on the results of the 4D BIM simulation on Batch and Activity levels. According to the final project report, this project was completed within 11.6 days.

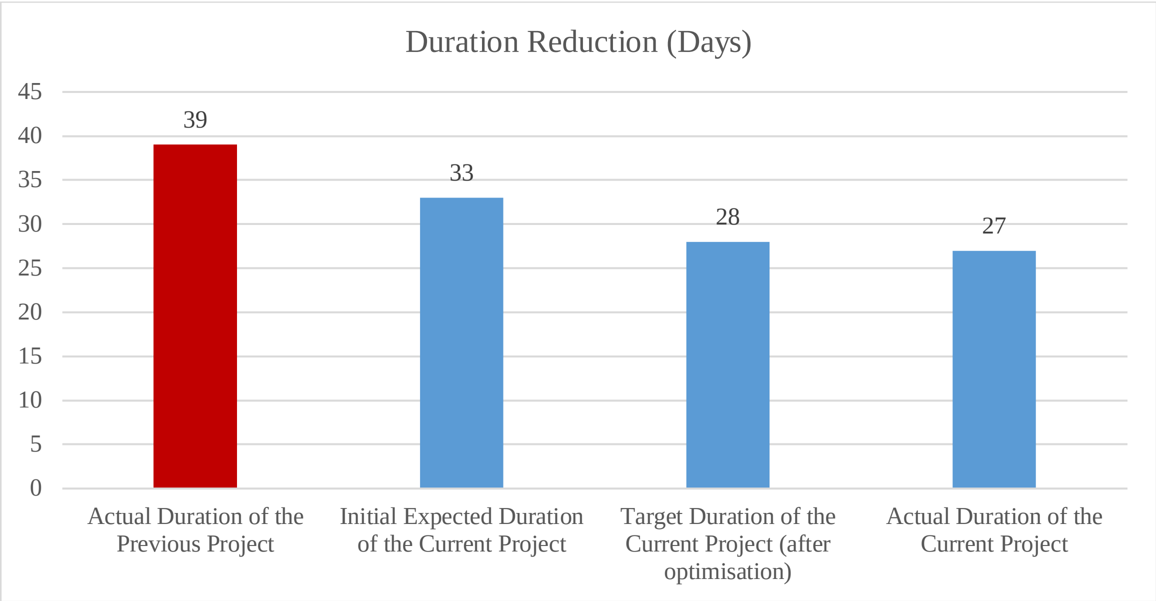

Figure 7-11: Duration Reduction Analysis

Based on a rough comparison, the field execution work was finished 0.4 day (i.e. 9.6 hours) before the target schedule and 1.9 days ahead of the initial plan. When compared with the previous equivalent one, a total of 2.4 days were saved. Excellent results were also achieved on the health and safety front, such as: 50% reduction in minor first aid cases, no environmental incidents, no medical treatment incidents, and no high potential incidents.

For cost reduction analysis, considering the inflation and the changing prices for instruments procurement and equipment leasing, it is meaningless to compare the actual cost of the two TAM projects. Figure 7-12 illustrates the project cost estimated at three different stages: initial stage, pre-execution stage, and completion stage, respectively. The initial budget (i.e. AUD$ 24.1 million) was estimated based on the initial work list and estimated duration. The budget before field execution (i.e. AUD$20 million) was calculated based on the final confirmed construction schedule and resource plans. The actual cost for this TAM project was AUD$ 19 million according to the project completion report.

A total of AUD$ 4.1 million was saved when comparing the actual cost with the initial budget. Specifically, AUD$ 4.1 million cost reduction was achieved during the project planning phase while another AUD$ 1 million was achieved during the project execution phase.

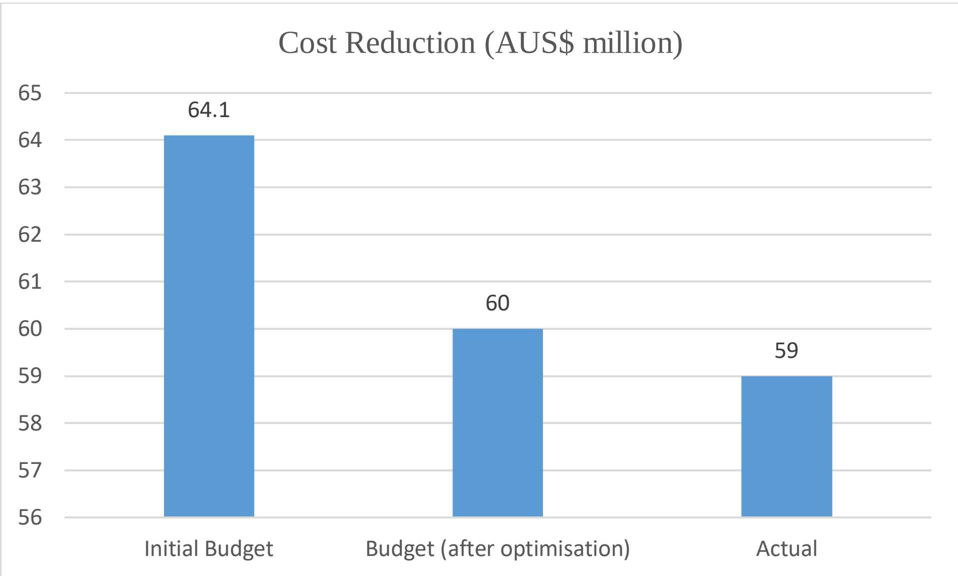

Figure 7-12: Cost Reduction Analysis

7.4.3 Analysis of the Contribution to the Time and Cost Reduction

It is unreasonable to attribute all the successful outcomes to the 4D BIM implementation. Other factors such as lessons learned from previous TAM projects also made a significant contribution to the project achievements. In order to understand the contribution of each factor, the TAM team conducted an internal focus group study after the turnaround. A total of 17 representatives from each discipline attended the focus group session. A few comments are highlighted as follows:

The turnaround manager said “One of the keys to the success of this turnarounds is the integration of the operations and maintenance teams’ activities to improve productivity and better focus on critical activities from stopping to restarting production”. The Operations team leader who in charge of more than 50 people for this turnarounds agreed with this point and indicated the importance of the Cloud BIM-based Clabouration Platform (i.e. descripted in Section 7.3.2, Chapter 7) that assured the maintenance and operation teams worked hand-in-glove. The turnaround site manager mentioned that "With the help of the 4D BIM Simulation on the Activity Level, the site work crews can efficiently understand their work scopes and sequences, and then, combining their site knowledge, paved the way to establish onshore best practices in both the planning and execution of LNG turnarounds". "Previous good practices were tabled, challenged and improved. We then utilised these together with the 4D BIM technology to help us with this turnarounds," remarked by the general maintenance manager.

The turnaround manager also highlighted another significant achievement of this project "Moreover, the turbine upgrade was completed two and a half days inside what is the global benchmark". The TAM emphasis also changed slightly mentioned by the general maintenance manager "Previously, the focus of a turnaround was on maintenance. But we've found that by maintenance and operations working together, we can focus on the window created by the production outage to split the work and optimise its sequence to better streamline it. Thus, splitting up the work on LNG 5 into discrete systems and prioritising critical path works enabled us to use a smaller nitrogen system which saved hundreds of thousands of dollars". A main conclusion from the focus group study was that every participant appreciated the value of the 4D BIM simulation. "The improvement facilitated by the 4D BIM includes: better planning of operations activities and understanding resource constraints, and the benefits from effective communications and closer teamwork". "4D BIM technology makes it possible to early engage with turnaround operators, so they knew exactly what they would be doing and when," explained by the turnaround manager.

Table 7-3 summarises the group discussion results. A total of 28 kinds of improvement were identified such as improvement in human training, permit sign-offs, and operation's team leader integration. These improvements were further classified into eight categories: (1) Human Logistics; (2) Operations; (3) Safety; (4) Inspections/Engineering Scope of Work/Communication; (5) Static/Valve Material Control; (6) Scope Development/Management; (7) Planning/Communication; and (8) Cost Estimation and Control. Specifically, out of the 28 kinds of improvement, twelve contribute to the time reduction, seven contribute to the cost reduction, five contribute to the both of time and cost reduction, and four contribute to the safety performance improvement.

The relationship mapping between the "Identified Improvement" and the "4D BIM Simulation" was also conducted by the focus group. Questions such as "For each improvement, is the 4D BIM the main driver?", "If the answer is yes, which level(s) of the 4D

BIM simulation should be attributed?", and "If the answer is no, what is the main driver of this improvement?" The right-most column of Table 7-3 illustrates the final results. 21 out of the 28 kinds of improvement are attributed to the 4D BIM implementation, especially in the categories of "Human Logistics", "Operations", "Scope Development/Management", and "Planning/Communication". The focus group also identified the specific level(s) of the 4D BIM simulation that contribute(s) to the improvement. For instance, the "4D BIM simulation on the Activity level" contributes to the improvement of "Human training" and "Human flight booking" because of the visual work package and time window developed for each site work crew. The other 7 kinds of improvement are attributed to the lessons learned from either previous TAM projects or sub-contractors. For instance, most of the improvement under the "Safety" category are achieved by applying learnings from other shutdowns. It does not mean the 4D BIM technology cannot have a significant impact on the safety performance because the 4D BIM simulation developed for this case is mainly focused on improving TAM planning and site work flow.

Table 7-3: Analysis of the Contribution to the Time and Cost Reduction

Identified Improvement	**Improvement Strategy**	**Contribution to?**	**Effect of 4D BIM Simulation**	
1. Human Logistics				
1.1 Flights o Communications o Early booking	Standardisation	Cost reduction	Yes	4D BIM Simulation on the Activity Level
1.2 Training o Complete training prior to onsite mobilisation	Standardisation	Time and Cost reduction	Yes	4D BIM Simulation on the Activity Level
2. Operations				
2.1 Procedure	Standardisation Dynamic pull flow	Time reduction	Yes	4D BIM Simulation on the Batch Level
2.2 Permit sign- offs	Standardisation	Time reduction	Yes	4D BIM Simulation on the System Level
2.3 Operation's team leader integration	Standardisation	Time reduction	Yes	All levels
3. Safety				
3.1 Dropped object	Standardisation	Safety	Yes	4D BIM Simulation on the Activity Level
3.2 Line of fire	Standardisation	Safety	No	Lessons Learned from Previous TAM

3.3 Bunting	Standardisation	Safety	No	Lessons Learned from Previous TAM
3.4 Radiography	Standardisation	Safety	No	Lessons Learned from Sub-contractors
4. Inspections/Engineering Scope of Work/Communication				
4.1 Standards/Cleaning requirement	Standardisation	Time reduction	Yes	4D BIM Simulation on the System Level
4.2 Waiting for fitness for service results	Standardisation	Time reduction	Yes	4D BIM Simulation on the Plant/System Level
4.3 People issues	Standardisation	Time and Cost reduction	Yes	4D BIM Simulation on the System Level
4.4 Review and agree testing technique for equipment inspections	Standardisation Dynamic pull flow	Time reduction	No	Lessons Learned from Previous TAM
5. Static/Valve Material Control				
5.1 Late ordering of valve components/shut down consumables	Location-based levelling	Time reduction	Yes	4D BIM Simulation on the System/Batch Level
5.2 Offsite repair/transport efficiency	Location-based levelling	Time reduction	Yes	4D BIM Simulation on the Batch Level
5.3 Valve and Static materials staging	Location-based levelling	Cost reduction	Yes	4D BIM Simulation on the System/Batch Level
5.4 Incorrect materials	Dynamic pull flow	Time and Cost reduction	No	Lessons Learned from Previous TAM
6. Scope Development/Management				
6.1 Work packs inconsistencies	Standardisation Location-based levelling	Time and Cost reduction	Yes	4D BIM Simulation on the Plant/System Level
6.2 Late change management for emergent work	Standardisation Dynamic pull flow	Time and Cost reduction	Yes	4D BIM Simulation on the System Level

6.3 Review/prioritise materials arriving post campaign start date	Standardisation Location-based levelling Dynamic pull flow	Cost reduction	Yes	4D BIM Simulation on the System/Batch Level
7. Planning and Communication				
7.1 Late issue/reports of pre-shut plans	Standardisation	Time reduction	Yes	4D BIM Simulation on the System/Batch Level
7.2 Offsite valve management	Standardisation	Time reduction	Yes	4D BIM Simulation on the Batch Level
7.3 Standard reporting milestones	Standardisation	Time reduction	Yes	4D BIM Simulation on the System Level
7.4 Inspection scope planning	Standardisation	Time reduction	Yes	4D BIM Simulation on the Batch/Activity Level
8. Cost Estimation and Control				
8.1 Costs forecast inaccurate from SAP	Standardisation	Cost reduction	Yes	All levels
8.2 WBS Structure early on Work Orders	Location-based levelling Dynamic pull flow	Cost reduction	Yes	4D BIM Simulation on the Plant/System Level
8.3 Clarify rolling average price, agreed process	Standardisation	Cost reduction	No	Lessons Learned from Previous TAM
8.4 Unable to return all unused materials to stock	Standardisation	Cost reduction	No	Lessons Learned from Previous TAM

7.5 Summary

In this chapter, a 4D BIM framework was developed for improving TAM process efficiency, which encompasses four different levels of BIM simulation, i.e. Plant, System, Batch, and Activity level. A real TAM project was selected to evaluate the effectiveness and efficiency of the proposed 4D BIM approach in waste elimination and time and cost reduction. The results show that: (1) The average transformation rate in terms of the five criteria (i.e. Total amount of cycle time, Total amount of processing time, The average percentage of on time start, VA ratio, and The number of interfaces) is 85%; (2) the TAM project starts on time and finishes 0.4 day (i.e. 9.6 hours) before the target schedule and 2.4 days ahead of the original schedule; (3) A total of AUD$ 4.1 million has been saved when comparing the actual cost with the initial budget; (4) 50% reduction in minor first aid cases, no environmental incidents, no medical treatment incidents, and no high potential incidents.

Chapter 8: Conclusions, Implications, and Future Recommendations

8.1 Conclusions

The aim of this section is to summarise the research findings in order to (1) draw unambiguous conclusions from the results; and (2) provide empirical evidence to demonstrate the capabilities of the developed methods. This section is organised according to the four research objectives formulated in Chapter 1.

8.1.1 Research findings for Objective 1

Objective 1

To obtain an in-depth understanding of the influencing factors by reviewing current VSM applications in multiple sectors.

Summarised Research Findings

- the VSM implementation in manufacturing, healthcare, construction, product development and service sectors were reviewed.
- the differences of the VSM implementations in the aforementioned five sectors and the reasons leading to the differences were investigated from four perspectives: the metrics applied to current state analysis, the tools used for future state improvement, the benefits achieved by the implementation (i.e. waste identification and quantification), and the critical success factors of VSM implementation.
- the key influencing factors to facilitate and improve VSM implementations in a TAM environment were identified, including:
    - ➢ value and waste definition in the specific TAM value stream environment is central to develop solutions for reduction;
    - ➢ the suitability and usability of lean metrics/techniques within the specific flow settings should be validated before adoption in the TAM environment.

Limitations

- Specific and predefined search criteria were established to include only peer-reviewed publications, although other types of publications may also contribute to the development of VSM theory and implementation.

8.1.2 Research findings for Objective 2

Objective 2

To standardise the definition and classification of VA and NVA activities in turnaround projects.

Summarised Research Findings

- A standardised VA and NVA classification system was developed to identify the value, waste, and its relevant root causes in TAM processes.
- The definition of VA and NVA in TAM project was clarified by following the value definition in TAM management: value is related to the successful completion of the maintenance activities assigned to trade crew. Waste was defined as an activity that represents a potential risk to the plant reliability and maintenance operation efficiency. The seven types of wastes were identified within the TAM project environment (Detailed explanation can be found in Table 5-1, Section 5.3).
- A standardised VA and NVA classification for TAM project was developed. The classification system included main tool activities in VA; supportive activities for tool operation, supportive activities for critical resources, critical safety checking activities, critical quality inspection activities, and permit authorisation in NVA. The activities in groups are separated into maintenance activities and relevant administrative activities.
- The proposed system was validated by conducting interviews with experts. The drafted classification framework was validated by capturing opinions of experts regarding the (1) epistemological adequacy, (2) reusability, and (3) reliability (Detailed explanation of these measures can be found in Table 3-3, Section 3.2.3). A sample process was used to evaluate the usefulness and consistency of the classification system.

Limitations

- The VA and NVA were defined and classified from only clients' perspective;
- The criteria adopted for validating the system were simplified and only included qualitative analysis.

8.1.3 Research findings for Objective 3

Objective 3

To develop an innovative Enhanced-VSM framework for a structured application into turnaround process.

Summarised Research Findings

- A five-step Enhanced-VSM framework was developed for facilitating lean application, which includes:
  - ➢ Critical work scope selection with three processes: network analysis, critical family unit identification, and target value stream selection.
  - ➢ Current state mapping and measurement with three processes, including definition and classification of VA and NVA in TAM workflow, mapping the maintenance execution process, and performance measurement.
  - ➢ Waste analysis to determine the causes that lead to variations from six categories and determine the magnitude of causes that lead to variations of processing time and start time.
  - ➢ Future state improvement with priority assessment of the waste identified and lean initiatives development.
  - ➢ Action Plan to explore the potential impact of the application in a virtual environment.
- A case study was conducted to demonstrate the capabilities of the proposed framework. Detailed results are listed as follows:
  - ➢ A target value stream can be successfully identified by using the rules proposed;
  - ➢ The current state analysis visualised the waste that results in variations in the process. 11.755 hours processing time variation was identified;
  - ➢ 18 root causes of the identified waste were systematically identified from 6 categories;
  - ➢ The top 10 causes of variations were identified, include error of tools, equipment, permit issue/isolation, delay of required material, challenge process, delay due to administration work, unplanned work, delay in crane availability, lack of skill/experience to perform the activity, unavailable

work front access, and other contractor interface conflict;

  - Three lean initiatives were proposed to reduce the waste.

- Significant overall improvement was obtained through the implementation:

  - The total processing time decreased from 49.15 hours to 40.19 hours.
  - The total amount of cycle time was reduced by 29.45 hours by scheduling the processing within locations.
  - The percentage of on-time start was increased from average 35% to 65% and VA ratio was increased from 49.33% to 60.37%.
  - The number of interfaces was reduced from 127 to 38.

Limitations

- Not all lean tools which can be used for eliminating waste were evaluated and tested.
- The framework was tested by using a single and representative case study.
- The selected case for validating the proposed framework was relatively simple because only the repetitive process is investigated.

8.1.4 Research findings for Objective 4

Objective 4

To investigate the capabilities of 4D Building Information Modelling (BIM) technique in improving Action Plan development and implementation.

Summarised Research Findings

- A 4D BIM framework was proposed for improving TAM process efficiency, which included four different levels of BIM simulation, i.e. Plant, System, Batch, and Activity level.
- A real TAM project was selected to evaluate the capabilities of the proposed 4D BIM framework in improving Action Plan development and implementation. Detailed results are listed as follows:

  - The average transformation rate in terms of the five criteria (i.e. Total amount of cycle time, Total amount of processing time, The average percentage of on time start, VA ratio, and The number of interfaces) was 85%, which means: (1) the Action Plan (i.e. the TAM project plan) generated from 4D BIM technique was effective; and (2) the Action Plan has been implemented accurately in the field.

- The TAM project started on time and finished 0.4 day (i.e. 9.6 hours) before the target schedule and 2.4 days ahead of the original schedule.
- A total of AUD$ 4.1 million was saved when comparing the actual cost with the initial budget.
- 50% reduction in minor first aid cases, no environmental incidents, no medical treatment incidents, and no high potential incidents

Limitations

- Only one single case study was conducted to validate the capabilities of the 4D BIM technique in improving Action Plan development and implementation

8.2 Summary of Theoretical Contributions

This research was motivated by tackling challenges of the application of lean production theory to improve process efficiency in TAM projects. The main theoretical contribution of this study include:

(1) A comprehensive review of VSM application in cross sectors that obtain an in-depth understanding of the influencing factors of efficient VSM application

Majority of current studies to discuss the use of VSM are within individual sectors. The use of VSM has not been sufficiently examined regarding its application in different production settings. Cross-sector comparisons and investigations in this thesis have provided detailed evidence of the differences of VSM implementations in various sectors. The theoretical contribution in this thesis consists of:

- *A complete review of the implementation cycle of VSM in the five sectors respectively*. The VSM application, including the metrics for current state map, improvement techniques for future state map, benefits and achievements of VSM application, and critical success factors for VSM implementation, was analysed.

- *Cross-sector comparisons and investigations on the four steps of implementation cycle of VSM*. The differences of VSM implementations and development were investigated by comparing the four steps of implementation in the five sectors. The reasons lead to the differences include un-adapted lean concepts; inconsistent features of the value streams; and inconsistent contexts of the flows.
- *Two key influencing factors for efficient VSM application*: understanding value and waste in a diverse value stream environment and ensuring the suitability and usability of traditional lean metrics/techniques within the different flow settings are central to the VSM development.

(2) A standardised VA and NVA definition and classification system for facilitating lean applications in TAM projects

Currently, the definition of VA is limited to physical transformation between manufacturing processes. This leads to a heavy focus on product characteristics only, such as functionality to satisfy the final users, which is related to whether an activity contributes to the form, fit or function of the production flow. In this thesis, it is argued that the traditional definition and classification of VA and NVA may not be applicable in TAM projects. In order to facilitate lean application in TAM projects, the standardised VA and NVA definition and classification developed in this thesis consist of two key aspects:

- *VA and NVA definition in TAM project*. Value was defined from the perspective of project client. It related to the successful completion of the maintenance activities assigned to trade crew. Value stream in maintenance process was identified. It is the transformation of maintenance activities, which centres upon maintenance staff who move from one functional maintenance to another with the assistance of resources, such as equipment, tools, materials, and information. Accordingly, VA is the group of activities that the trade crews contribute directly to the plant productivity. NVA but necessary includes the group of activities that have no direct contribution to the functions of the plant, but are critical to the maintenance process effectiveness and efficiency. There are two elements in this group: one is the activities to support effective maintenance operation, such as scaffolding erection and crane lifting; the other one is the activities to facilitate process efficiency, such as the required resources and specification that have been delivered/assigned to the right task at the right time. Waste is any activity that represents a potential risk to the plant reliability and maintenance operation efficiency.

- *VA and NVA classification in TAM projects.* The massive amount of maintenance activities were classified according to the further clarified VA and NVA definition. VA is the tool activities, which are related to the execution conducted by operation and engineering teams, and includes the main maintenance operations work, such as isolation removal and flange unbolt, physical work on all or part of a plant. The activities in NVA are further divided into five groups based on their functionalities: including (1) supportive activities for tool operation, which are related to the activities conducted by contractors to support and facilitate the execution of main tool activities; (2) supportive activities for critical resources, which refer to the activities that are performed to deliver/transfer/assign the right resources to the right WPs; (3) critical safety checking activities, which are related to the activities that contributed to the safe execution of maintenance; (4) critical inspection activities; and (5) permit authorisation, which is mandatory before operation. Seven types of waste were identified in TAM project environment. The case study in Chapter 5 demonstrated the power of the classification system in detecting value and waste in both maintenance and administrative activities.

(3) An Enhanced-VSM application framework that enhances the applicability of lean tools within turnaround project environment

Current VSM application follows the practical procedures developed for manufacturing processes. Some of the unique features of the project-based production system may impede the direct VSM application. The enhanced-VSM framework proposed in this thesis tackles the four main challenges of VSM implementation in the TAM environment, including work scope selection, current state measurement, waste analysis, and lean tools selection for eliminating the waste. The case study discussed in Chapter 6 demonstrates the power of this framework in selecting the critical work scope, extracting important process information, identifying and prioritising the root causes, and adopting the lean tools.

8.3 Practical Implications

This thesis represents an effort to help project client in the oil and gas industry improve operational efficiency in VSM application including VSM review and analysis, VA and NVA definition and classification, structured VSM application procedures and 4D BIM simulation framework for facilitating Action Plan development and implementation.

The developed standardised VA and NVA definition and classification framework provides a guideline for project clients to efficiently manage VA and NVA during the operation of TAM projects. At the time of this study, few VSM implementations in TAM projects have been identified. The standardised classification system can help project planners and clients efficiently identify the NVA and waste in the process of TAM projects and make sure they are timely eliminated or reduced.

The proposed enhanced-VSM framework provides a detailed step-by-step instruction in terms of VSM application in TAM projects. By applying the framework developed in Chapter 6, project clients can not only identify the most critical operation process and the root causes of these waste, but also select and adopt the appropriate lean tools to eliminate the specific waste. The case study discussed provides a useful guideline for industry people to implement these steps.

The proposed 4D BIM-enabled approach for improving Action Plan development and implementation, detailed in Chapter 7, provides an efficient way for turnaround managers to transform current state VSM to future state VSM. The 4D BIM simulation on the plant level can effectively support the engagement of the project core teams (i.e. Operations, maintenance & Integrity, and Turnaround Lead) to review the project scope. The 4D BIM simulation on the system level can support the engagement of teams of Planning, Work Pack Development, Engineering, and Procurement to: (1) communicate and review terms of reference, discuss initial risks, functional requirements, likely resources and establish delivery strategy; and (2) review initial scope against turnaround acceptance criterial, prioritise tasks and establish initial work list. The 4D BIM simulation on the batch level can support the engagement of external contractors and/or out-of-plant personnel to evaluate the critical path, and come up with alternative execution methods to shorten the project duration. The 4D BIM simulation on the activity level can ensure that all parties understand the work to be done and the sequence and details of the shutting-down process together with preparation for entry.

8.4 Recommendations for Future Research

According to the limitations summarised in Section 8.1, recommendations for future research and development can be carried out as follows:

(1) Investigating the definition and classification of value and waste from different viewpoints

It is pointed in Chapter 5-4 that future research should explore the understanding and classification of VA and NVA activities from different viewpoints, such as operation contractors and resource vendors. This research provides the information for future research of the potential challenges that prevent the efficient interactions between clients, contractors, and vendors.

(2) Reviewing the lean production tools and techniques on the application in for TAM context

It is suggested that the focus on the selection of lean production tools and techniques for project-based production context should be conducted with a comprehensive analysis. The review gives a general understanding of the features, pros, and cons of the selection and implementation of lean tools and techniques for improving process efficiency in TAM project. The development of lean application in oil and gas industry can be leveraged by identifying the critical factors that affect the selection process of appropriate lean production tools and techniques.

(3) Implementing the enhanced-VSM framework in real TAM projects in oil and gas industry

The enhanced-VSM framework developed in Chapter 5 and 6 should be tested with more case studies in the oil and gas industry. This would help evaluate the wider applicability as well as creating best practices for future implementation of VSM in TAM projects. The wider application provides explanations of how the performance of TAM operation can be improved through the application of VSM and relevant lean tools.

(4) Investigating the simulation tools that have been used for evaluating the performance of lean implementation

To further advance research in the area of simulation-based lean implementation and to improve the effectiveness and efficiency of the simulation tools, future research should be carried out on reviewing different simulation tools that can be used to analyse the efficiency of lean implementation. There is a necessity to discuss the main features and best practices of the different simulation tools used in the simulation-based lean research. This research can provide the information that is necessary to identify the suitable simulation tools to maximize lean benefits in a specific environment.

APPENDIX: LIST OF PUBLICATIONS

A. Journal paper

1. **Shou, W.**, Wang, J., Wu, P., Wang, X., & Chong, H. Y. (2017) A cross-sector review on the use of value stream mapping. *International Journal of Production Research*, *55*(13), 3906-3928.
2. Wu, P., Song, Y., **Shou, W.**, Chi, H., Chong, H. Y., & Sutrisna, M. (2017) A comprehensive analysis of the credits obtained by LEED 2009 certified green buildings. *Renewable and Sustainable Energy Reviews*, *68*, 370-379.
3. Wang, J., **Shou, W.**, Wang, X., & Wu, P. (2016) Developing and evaluating a framework of total constraint management for improving workflow in liquefied natural gas construction. *Construction Management and Economics*, *34*(12), 859-874.
4. Wang, J., Wang, X., **Shou, W.**, Chong, H. Y., & Guo, J. (2016) Building information modelling-based integration of MEP layout designs and constructability. *Automation in Construction*, *61*, 134-146.
5. **Shou, W.,** Wang, J., Wang, X., & Chong, H. Y. (2015) A comparative review of building information modelling implementation in building and infrastructure industries. *Archives of computational methods in engineering*, *22*(2), pp291-308.
6. Wang, J., Zhang, X., **Shou, W.**, Wang, X., Xu, B., Kim, M. J., & Wu, P. (2015) A BIM-based approach for automated tower crane layout planning. *Automation in Construction*, *59*, 168-178.
7. Wang, J., **Shou, W.,** Wang, X. and Chi, H.L. (2015) An Integrated Approach for Progress Tracking in Liquefied Natural Gas Construction. In *Cooperative Design, Visualisation, and Engineering*, pp. 259-267

B. Book Chapter

1. Wu, P., Wang, J., **Shou, W.,** & Wang, X. (2017) BIM-Integrated Life Cycle Assessment in Environmental Analysis–Current Status and Future Development. Integrated Building Information Modelling, 224.

C. Conference Papers

1. **Shou, W.,** Wang, J., Wu, P. , Wang, X. & Song, Y. (2017) Application of Lean Production With Value Stream Mapping to the Blasting and Coating Industry, *25th*

Annual Conference of the International Group for Lean Construction. Heraklion, Greece, 9-12 Jul 2017. pp 217-224

2. **Shou, W**., Wang, J., Wu, P., and Wang, X., (2017) An enhanced value stream mapping approach for plant turnaround maintenance project. *The 3rd ICCBEI in conjunction with 2017 CCACHE*, Taipei, Taiwan, 19-21 April 2017
3. Wang, J., **Shou, W.**, Wu, P., & Wang, X. (2017) Linked Data for Cross-domain Constraint Information Sharing in LNG Construction. *LC3 2017: Volumn I-Proceedings of the Joining Conference on Computing in Construction (JC3)*, Heraklion, Greece, July 4-7, pp. 811-818.
4. **Shou, W.**, Wang, J., Wang, X. & Chong, H. (2016) Examining the Critical Success Factors in the Adoption of Value Stream Mapping, *24th Annual Conference of the International Group for Lean Construction*. Boston, USA, 20-22 Jul 2016.
5. **Shou, W.**, Wang, J., Wang, X. and Chong, H.-Y. (2015) An application of value stream mapping for turnaround maintenance in oil and gas industry: Case study and lessons learned, *Procs 31st Annual ARCOM Conference*, Lincoln, UK, Association of Researchers in Construction Management, 7-9 September 2015, 813-822.
6. Wang, J., **Shou, W.** and Wang, X. (2015) A framework of total constraint management for improving work flow in liquefied natural gas construction, *Procs 31st Annual ARCOM Conference*, Lincoln, UK, Association of Researchers in Construction Management, 7-9 September 2015, 803-812.
7. **Shou, W.,** Wang, X., Wang, J., Hou, L., & Truijens, M. (2014) Integration of BIM and Lean Concepts to Improve Maintenance Efficiency: A Case Study. *Computing in Civil and Building Engineering* ASCE, pp. 373-380
8. **Shou, W.,** Hou, L. Wang, J., and Wang, X. (2014) Case Studies of BIM-based Dynamic Scaffolding Design and Safety Prevention, *2nd International Conference on Civil and Building Engineering Informatics (ICCBEI 2015)*, Tokyo, Japan, 22 – 24 April

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