STRATEGIES TO MINIMIZE CONSTRUCTION DELAY: MATHEMATICAL ANALYSIS

BY

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ABSTRACT

Construction project delay has become a menace contending with the construction sector opposing time, cost, and quality. It is a problem that thrives throughout the stages of the project thus debasing quality and performance. This study, which collates experts' opinions from "Thai construction sector on the degree of influence of each key delay factors on the other, establishes the prominence (influence) level, dynamics, and impact of the controlling factors of construction delays on project schedule using a hybrid mathematical system (DEMATEL-SD modelling). Five key delay factors in this study include Design Error, Rework, Change Order, Design Change, and Productivity factors. DEMATEL analysis concludes that though all the factors are influencing but their influence levels differ. It is discovered that Rework is the most influencing factor of construction delay with a prominence value of 56.5134 and an influence degree of 20.1198%, and has mutual relationships with Design Error, Change Order, and Productivity. Design Error, which has a prominence value of 55.5492 and an influence degree of 20.1198%, is the second influencing factor, and has mutual relationships with Change Order, Rework, and Productivity. Change order is the third influencing factor with prominence value of 55.2156 and influence degree of 19.9990%. It influences Productivity, and has mutual relationships with Design Error, and Rework. Productivity is the fourth influencing factor with prominence value of 55.0712 and influence degree of 19.9467%. It has mutual relationships with Design Error and Rework. Design Change is the fifth influencing factor with a prominence value of 53.7428 and influence degree of 19.4655%. This factor is influenced by Rework and Productivity. System dynamics (SD) modeling is then employed with the DEMATEL analysis results, forming the so-called DEMATEL-SD model, to comprehensively explore the dynamics of the factors and their impact on project schedule. The simulation results reveal the importance of reducing Design Error in the pre-construction stage to minimize the magnitudes of Change Order, Design Change, and Rework during construction, which in turn, enhance the Productivity in the post-construction stage and reduce project delay in succession of time. Rework, Design Change, and Change Order must be closely monitored during the construction to ensure work productivity and on-time project completion. The results also reveal that experienced designers and uses of updated and integrated design software help reduce design errors, thus enhancing work performance in the long term. Other improvements, such as effective supervision during construction, payment system, contractor's experience, owner's decision system, good project management and cooperation key stakeholders, including owners, consultant, and contractors also assist in reducing the construction delay in the long term.

Keywords: Change order, Construction, Delay, DEMATEL, Design change, Design error, Pre-construction, Post-construction, Owner, Productivity, Rework, System dynamics

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LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	**Terms**
DE	Design Error
DC	Design Change
CO	Change Order
R	Rework
P	Productivity
TA	Technology Accuracy
PS	Project Supervisors
PM	Project Management
DP	Delayed Payment
Old	Owner's Late Decision
CE	Contractor's Experience

CHAPTER 1
INTRODUCTION

1.1 Background of Study

The process of constructing a building or infrastructure is known as construction (Laws, 2019). The "economic activity directed to the creation, renovation, repair or extension of fixed assets in the form of buildings, lands improvements of an engineering nature, and other such engineering constructions as roads, bridges, dams and so forth" (UN Statistics Division, 2022). A project, on the other hand, is a chain of a similar tasks, which when carried out in the correct order, leads to the completion of the project. Therefore, a construction project is referred to as the organized process of constructing, renovating, and refurbishing a building, structure, or infrastructure (Designing Building, 2021). Construction projects are highly structured endeavors with regular and great dynamics that require high level of coordination from participants to capture the workflow. Buildings, infrastructure, and industrial are three basic types of construction (Ogano, 2016). Projects could also be separated into small, medium, and large size (Ogano, 2016). Project complexities often increase with project size, and that effective project management is essential to handle the associated complexities for better project performance.

Asia is the world's fastest growing part, with the construction sector having the greatest impact on its future growth (Aditya Group, 2020). In Thailand, the sector plays a leading role in the economy of the country. Over the years, Thai construction industry recorded a solid annual growth of 15.8%, contributing up to 2.8% of the total GDP (Aditya Group, 2020). The government allocated around $100billion for several infrastructure development from 2014 to 2021. This makes the construction industry a giant sector with a number of large-scale infrastructure projects that enhance the development of other sectors (Aditya Group, 2020; Venkatesh & Venkatesan, 2017). The role of the sector in the economy cannot be overemphasized coupled with its activities which are also vital to the achievement of national social-economic development goals. Aibinu and Jagboro (2002) stressed that the contributions of the construction industry to the national economic growth and cost savings necessitate improved efficiency in the industry by means of cost-effectiveness and promptness. This sector plays a key part in the improvement of income per capital, thereby engaging significant proportion of the active work force through availability of job opportunities (Malaj & Shuli, 2015). It provides essential structures, such as private and public infrastructures and housing, thereby, fulfilling human being's major requirements (Imad et al., 2018; Kirchberger, 2018; Chimay et al., 2008). The quest to promote socio-economic development has compelled the government to invest significant amount in infrastructure systems (Andric et al., 2019). This explains the fact that the significance of infrastructure as a function of the construction sector is highly recognized by extant investigators. Ogunlana et al. (1996) stressed that Thai construction sector experienced a massive growth with the construction of condominiums, hotels, and shopping centers, fostering the growth of country's economy. Hicham et al. (2016), in the same way, mentioned that Moroccan construction industry has immensely contributed to the drastic reduction of unemployment rate. The industry shares average of 6.6% of the gross domestic product (GDP), representing 50.1% of the gross fixed capital formation (GFCF). Subramani et al. (2014) claimed that Indian construction sector has contributed to the improvement of the living standard of the people through massive employment. This industry which is the largest employment sector in the country, employs 31 million people, and accounts for up to 8% of GDP. Other economies like Ghana (Boadu et al., 2020), UAE (Cherian, 2020), Malaysia (Memon et al., 2012), Zambia (Aigbavboa et al., 2002), Saudi Arabia (Assaf et al., 1995), Nigeria (Mansfield et al. 1994), among others, are not left out of the positive impacts of the construction sectors. This leads to the magnitude of the global construction industry, which is approximately 40% of GDP, and is expected to be doubled within the next 30 years" (Solis, 2007).

1.2 Construction Delay

Though the construction industry "contributes positively to the economy, an opposing phenomenon and complications of the construction sector is delay, which reflects poor project performance (Jalal & Yousefi, 2017; Gardezi et al., 2014; Yang & Tsai, 2011; Bertelsen & Sacks, 2007; Sambasivan & Soon, 2007). To successfully conduct construction projects, construction delay should be considered, as it significantly affects time and cost of projects (Sweis et al., 2008).

Construction delay is referred to as event leading to extension of time to complete specific assignments (Sambasivan & Soon, 2007). Desai and Bahtt (2013) defined delay as the time extension in date that the parties agreed upon for delivery of a project. Recently, even with the advancement of technology, project participants' knowledge of modern technology, and management techniques, construction projects still suffer delays. Project completion dates still get pushed back, reflecting that delay is crucial to project success (Stumpf, 2000). In Saudi

Arabia, only 30% of construction projects were completed within schedule, and the average time overrun was between 10% and 30% (Assaf & Al-Hejji, 2005). Odeyinka and Yusif (1997) stated that seven out of ten surveyed projects in Nigeria suffered delays. As time is a major part of every construction plan and can affect each part's contractual obligations, delay must be minimized to avoid time and cost overrun (Gardezi et al., 2014).

Several negative effects of delays have been identified by extant researchers. Tafazzoli and Shrestha (2017), for example, opined that construction delay has a deleterious effect on all triple-bottom lines of sustainability (social, environmental, and financial). Delay in construction causes time overrun, leading to excess cost. Time overrun, cost overrun, reduction in profits for contractor, losses for owner due to extended construction phase, distrust between owner and contractor, legal disputes between various parties, and total abandonment of project are the direct effects of delay (Hassan et al., 2017). Gebrehiwet and Luo (2017), on the other hand mentioned that cost overruns, termination of contract, arbitration, and litigation are critical consequences of delay. Ametepey et al. (2017) stated that delay results in time overrun, cost overrun, delay by contractor in repayment of loans, disputes, and poor quality of work due to speeding up of work. Fashina et al. (2020), Ullah et al. (2018), Udasi and Darade (2018), Khattri et al. (2016), Haseeb et al. (2011) agreed that dispute, cost overrun, time overrun, abandonment, negotiation, lawsuit, litigation, total desertion are effects of delay".

1.3 Problem Statement

Dolage et al. (2009) and Rahman (2018) emphasized the importance of highlighting root causes of construction delay to avoid time and cost overruns. The quest "to identify the causes of delay to assuage its threat, and its negative effects, has necessitated myriads of investigations over the years. Design changes and low productivity are, for example, mentioned as causes of construction delay (Venkatesh & Venkatesan, 2017; Lessing et al., 2017; Aziz, 2013). Eksander (2018) mentioned that financial difficulties from owners and contractors affect project completion time. Labor and materials are also key resources necessary for on-time project delivery (Desai & Bhatt, 2013). Tahir et al. (2019) also studied delay and cost overrun causes in Malaysian construction projects, while Gardezi et al. (2014) investigated time extension factors in construction industry of Pakistan. Other studies on causative factors of delay include Shahsavand et al. (2018), Ikechukwu et al. (2017), Samarah and Bekr (2016), Kesavan et al. (2015), Aziz (2013), Sweis (2013), Mohammed and Isah (2012), Toor and Ogunlana (2008), Alaghbari et al. (2007), Sambasivan and Soon (2007), Imad et al. (2018). Results of these investigations reveal key construction delay factors and their importance scores. However, the problem of construction delay still lingers till present, buttressing the fact that the effective panacea to this monumental problem goes beyond identification of factors, and there is a need to step up the quest in mitigating this problem. The convolutions among these controlling factors and their changes with respect to time, should be explored to investigate their impacts on the entire project scheme.

1.4 Research Aim and Objectives

The aim of this research study is to investigate the impact of controlling factors of construction delay on project schedule across the project stages (i.e., preconstruction, construction, and postconstruction stage) through the intricating relationships among the spanning and controlling factors. The study first identifies key delay factors to get stakeholders acquainted with and wary of key delay factors. The judgmental opinions of experts with reasonable number of years of experience in the Thai construction sector were harnessed and explored to collate the key factors. The key objectives of this study are listed as follows:

- To apply the Decision-Making Trial and Evaluation Matrix (DEMATEL) analysis system to compute the prominence, influence weight, and cause-effect relationships among the key delay factors using data from construction experts.
- To develop a system dynamics (SD) conceptual model based on DEMATEL analysis results, so-called the DEMATEL-SD model to examine the dynamics behaviors of construction project delay in Thai construction sector and their effects over time.
- To perform policy analysis to generate policy scenarios for Thai construction sector to be used to make long-term implementation plan to reduce the construction delay.

1.5 Research Questions

This research seeks to answer the following questions:

- What are the project dynamics factors in the Thai construction industry?
- How do the key delay factors and other elements interact with each other in a dynamic project set up?
- What policy scenarios derived from the resulting model are available that can help project stakeholders in the construction sector to achieve timely project delivery, thus enhancing better project performance?

1.6 Motivation of Study

Management of projects is challenging as a result of rising uncertainties. These uncertainties are functions of project delay that decrease the construction performance (Ogano, 2016). Government and individual firms, attempt to improve time performance to avoid cost overrun. Project management has become the center of active organizations. However, as complexities of projects increase, project failure becomes high (Pugh Robert Associates, 1993). Time and cost overruns are common phenomena in the construction industry, as many projects falter and are often completed later than schedule or over budget or are cancelled prior to their completion after spending considerable amount of money. While problems encountered in construction projects are dynamic, they have been treated as static problems within a partial view of a project (Lyneis et al., 2001). Owing to these, schedule delay is a common phenomenon rocking the spate of the construction sector despite the advancement of construction equipment (Park & Pena-Mora, 2003).

The motivation of this study is to comprehensively explore the dynamics of the delay factors to investigate the impacts of the controlling parameters (key factors of delay) on project schedule, thus fostering the understanding of the dynamic relationships among the delay factors and the complexities involved in construction projects. This understanding is captured in a DEMATEL-SD model of delay factors at different phases of construction projects. It is expected that the developed model suggests suitable policies to abate project delays in the construction industry in the long term.

1.7 Scope and Limitations of the Study

This study is directed towards subjugating the menace of schedule delay by investigating the impact of controlling parameters on project schedule. The research encapsulates the perspectives of key players who are decision makers in the Thai construction sector through interviews and data collection process. Majority of the experts have minimum of ten years of experience in the industry. The prevailing conditions of the Thai construction sector are used as a benchmark for other emerging economies. Therefore, it is presumed that the DEMATEL-SD model developed in this research will help project participants to make an effective decision to minimize the project delay. The results of this study are presumed to be beneficial to other emerging economies across the globe.

1.8 Significance of Study

This study examines the impact of each factor on the entire project schedule by minimizing delay right from the preconstruction stage, through extensive investigation of the design error, followed design change, change order, rework, and productivity cycle leading to minimization of construction delay. These signify an effective way to mitigate the potency of these parameters in course of the construction project, and rapidly reduce the magnitude of time overrun in the long term.

Project delay is a menace that evolves over time. The study results are expected to improve project performance through comprehensive understanding of the dynamics involved in construction project from preconstruction stage to the postconstruction stage. The results will be beneficial to other emerging economies sharing the same operating characteristics and environments across the globe. The results will also be useful for designing new projects and help key players in effectively handling the delay factors to minimize delay, reduce cost overruns, and improve economic growth.

1.9 Organization of Research/Findings

The research comprises of six chapters. Chapter one highlights the problem statement, research aim and objectives, motivation, scope and limitation, and significance of study. Chapter two conducts a review of literature related to construction delay to capture previous research findings and present trends in the study area. Chapter three explains the research methods, data collation system, and demography of respondents. Chapter four describes the DEMATEL analysis of construction delay factors to achieve the prominence, influence weight, and the cause-effect relationship of key delay factors. Chapter five utilizes the DEMATEL analysis results as input into the SD model development to examine the dynamics of the controlling factors of delay and impact of the controlling parameters on project schedule over time. Policy analysis to minimize construction delay in the long term” is also presented in this chapter. Chapter six concludes and summarizes the entire research.

CHAPTER 2
REVIEW OF LITERATURE

2.1 Background Information

This chapter explores and reviews the literature and theory of construction delay. Key construction delay factors are extracted and examined at the end of the chapter.

2.2 Construction Stages

Rao et al. (2016) mentioned that “construction activities are divided into three phases, pre-construction, construction, and post-construction phases. The preconstruction phase of a project is very important, as it has great effects on the schedule performance. This phase is embedded with several levels of uncertainties, and consists of several activities, some of which are project opening, designing, bidding, and work preparation (Rao et al., 2016). At this stage, owner should provide formal approach for cost development, scope, and schedule to execute timely construction. It is also the stage where the foundation of project communication is laid. The construction phase (so-called execution phase) transforms work design into physical structure. At this stage, people tend to associate with construction projects partially due to its visibility. The contractor transitions the project into actual construction, while the consultant engages in full construction administration services to perform quality control inspections, respond to Requests for Information (RFIs), review and approve technical submittals and generally ensured that the project is delivered by the contractor as scheduled (Stonemark ,1997). With the aid of new technology, owners and consultants can gauge progress and jobsite activities (Ridell, 2017).

Closeout phase, on the other hand, encapsulates activities to hand-in the project. This final phase has often been neglected, making it difficult to close out the project on time. Even the project that proceeds according to schedule could faulter towards the end due to administrative, technical, or financial reasons (Kaul, 2014). This phase includes completion of the punch list-turning over the scheme to the client for occupancy or operation. Clients should be provided all information, a construction closeout document list, and all closeout documents such as manuals, warranties, as-builts and final accounting (Stonemark, 1997). Therefore, it is important for project stakeholders to be careful in handling activities at this phase and even the preceding phases, as poor implementation of each phase could lead to construction delay and cost overrun. Main activities in each phase are listed in Table 2.1.

Table 2.1 Main activities in each phase of construction projects (Nikumbh & Pimplikar, 2014)".

Phase	Activity
Pre-construction	• Analyze client's project specifications • Prepare the design brief in terms of function ability, cost, time, quality, and safety • Develop project control systems • Finalize schedule organization guide • Establish scheme imparting structure • Prepare work breakdown structure • Control cost during design processes • Prepare procurement plan • Review technical specifications and bill of quantities • Monitor the statutory approval process and report the progress • Conduct pre-bid meetings and feedback for completeness of tender specifications and technical parameters • Compare statements and techno-commercial evaluation reports • Submit weekly and monthly progress reports
Construction	• Supervise all construction work/ activities • Coordinate on-site design • Organize approval to contractors' shop drawings, product data sheet, and samples • Refine work breakdown structure • Monitor work progress • Detect anticipated bottlenecks • Correspond with daily contractual issues • Change order management for design changes and extra items • Prepare quality assurance/quality control scheme • Assurance quality control to conform with drawings and specifications • Initiate environmental, health and safety (EHS) plan

	• Issue good for construction (GFC) drawings to respective contractors, and update record issued regularly • Inspect working drawings received from architects/designer • Organize weekly review meetings • Peruse records of contractors' daily progress reports
Post-construction	• Advice about probable date of substantial completion • Prepare and address the schedule of defects/ punch lists • Help in testing and commissioning of the facility • Collect and integrate various operation and maintenance manuals, commissioning, and test certificates • Reconcile and certify final bills of contractors, suppliers, vendors, and consultants • Prepare project close-out report • Collate and verify all As-built drawings • Address any queries during defects liability period ▪ Co-ordinate with contractors to rectify defects during the defect's liability period

2.3 Construction Delay Factors

Construction delay has been the main problem of construction parties to deliver a project on time. Research has been performed "in the past years to better understand construction delay from various perspectives. Owners, consultants, and contractors play important roles, as they are involved from the beginning to the end of projects. Khoso et al. (2019), for example, mentioned that the owner's selection of a project team is crucial to avoid delays. The scope of work should be clearly understood between the owners and consultants. An updated list of materials must be provided to avoid erroneous material specifications. Clear communication among the design team members is also required to reduce change orders, which might lead to unnecessary delays. Contractors should hire experienced workers to reduce rework and enhance productivity (Staiti et al., 2016).

Several investigations have been carried out in both emerging and developed economies to identify the causes of delay with different methods of solutions. In developing countries, for example, Comorde and Dickson (2019) mentioned exorbitant rental charges on construction equipment as a main cause of project delay. Archarya et al. (2006), on the other hand highlighted frequent equipment breakdown, changed site condition, and unrealistic project time estimation as responsible factors of project delay. Abbasi et al. (2020) mentioned that delayed payments, unrealistic schedules, and shortages of skilled workers are critical delay factors in the Iranian construction industry. Tahir et al. (2019) investigated causes of delay in the Malaysian construction industry, and concluded that delays in material delivery, contractor lack of experience, shortages of labor, and scope change are major delay causes. Eksander et al. (2018) showed that insufficient client funds, contractor cash flow, economic climate, and design change are key construction delay factors in Saudi Arabia. Mittal and Paul (2018) concluded that delays in work rotation, contingency work, and change orders are major construction delay factors. Kazaz et al. (2012) identified design changes, delayed payments, cash flow problems, poor productivity, and poor human resource planning as key delay factors in Turkey. Toor and Ogunlana (2008) mentioned a lack of resources, poor management, shortage of labor, design problems, planning and scheduling, change orders, and contractor financial difficulties as causes of delay in Thailand.

Construction delay is also crucial in developed countries. Arantes and Ferreira (2020), for instance, highlighted improper planning, consultant poor performance, inefficient site management, client influence, and sub-standard contracts as controlling factors of delay in Portugal. Bahra (2019), in contrast, identified that scope changes, change orders, conflicts, and poor monitoring are technical challenges accounting for delays in the United Kingdom. Zidane and Andersen (2018) concluded that improper design, poor planning and scheduling, resource shortages, design changes, and variation orders are the reasons for delay in Norway. Tafazzoli et al. (2017) mentioned that change orders, slow owner decisions, design errors, and late approval of design documents contribute to construction delays. Larsen et al. (2016) concluded that financial problems, poor project planning, and construction errors are key delay factors in the Danish construction industry.

Despite series of investigations that have been carried out in identifying the causes of delay, the problem persists. Therefore, there is a need to systematically identify the key controlling delay factors which forms the basis of a holistic investigation for stakeholders to get acquainted with the key factors of delay, and to effectively investigate the dynamics behaviors involved in the construction projects. This would, in turn, enhance the effective investigation of the impact of the key factors on the entire project schedule. It is discovered that many of these key factors enhance project time lag through some other key factors. For example, improper construction method, procurement and payment system initiate the menace of change order (Khoso et al., 2019; Alaryan, 2014). Conflicts between project stakeholders, quality of material, and lack of skilled workers lower the work productivity (Karthik & Rao, 2018; Moradi et al., 2017).

Experts in the industry corroborate the fact that many underlying factors lead to project delay or have direct effects on other factors in causing delay. In this study, therefore, construction delay factors associated with both developed and developing economies, are collected from the existing literatures and are later verified by experts in the Thai construction industry (see Table 2.2). It shows five key construction delay factors, which are the direct effects (dependent variables) of several frequently mentioned delay factors in the literature (independent variables). They are Design Error, Design Change, Change Order, Rework, and Productivity.

Table 2.2 Key factors affecting construction delay

Independent Variable (Cause)	Dependent Variable (Effect)	Country of Study	Reference
• Poor communication and coordination • Consultant's lack of experience • Technology usage	Design Error (DE)	Iran, Malaysia, Norway, Portugal	Abbasi et al. (2020), Arantes and Ferreira (2020), Zidane and Andersen (2018), Fuadie et al. (2017), Shamsudeen and Obaju (2016), Najafabadi and Pimplikar (2013), Couto (2012), Love et al. (2012), Suther (1998), Interview.
• Shortages of materials • Owner's late decisions	Design Change (DC)	Egypt, Ethiopia, Iran, Jordan, Malaysia, New Zealand, Nigeria, Norway, Portugal, Saudi Arabia, Turkey, USA	Bassa et al. (2019), Eksander (2018), Zidane and Andersen (2018), Gebrehiwet and Luo (2017), Lessing et al. (2017), Tafazzoli and Shrestha. (2017), Samarah and Bekr (2016), Arantes et al. (2015), Suleiman and Luvara (2016), Yana et al. (2015), Memon (2014), Owolabi et al. (2014), Aziz (2013), Najafabadi and Pimplikar

			(2013), Kazaz et al. (2012), Mirshekarlou (2012), Sun and Meng (2009), Interview.
• Lack of sufficient data before design • Owner's lack of experience • Inadequate planning and scheduling • Mistakes in producing design documents • Rigidity of consultant • Complexity in project design • Owner's change in requirements • Late procurement • Improper construction method by contractor • Difficulties in financing projects • Change in material types during construction • Owner's financial problems • Delayed payments	Change Order (CO)	Denmark, Egypt, India, Iran, Jordan, New Zealand, Nigeria, Norway, Finland, Portugal, Thailand, UK, USA	Abbasi et al (2020), Arantes and Ferreira (2020), Bahra (2019), Jusilla and Lahtinen (2019), Khoso et al. (2019), Mittal and Paul (2018), Shahsavand et al. (2018), Zidane and Andersen (2018), Lessing et al. (2017), Tafazzoli and Shrestha. (2017), Samarah and Bekr (2016), Larsen et al. (2016), Alaryan et al. (2014), Aziz (2013), Halwatura and Ranasinghe (2013), Najafabadi and Pimplikar (2013), Al-Hams (2010), Keane et al. (2010), Toor and Ogunlana (2008), Aibinu and Odeyinka (2006), Ahmed et al. (2003), Interview.
• Poor supervision	Rework (R)	Egypt, Ethiopia, Iran, Jordan, Portugal	Arantes and Ferreira (2020), Mahamid (2020), Chandrusha and Basha (2017), Enhassi et al.

• Poor project management			(2017), Gebrehiwet and Luo (2017), Abeku et al. (2016), Mahamid (2016), Samarah and Bekr (2016), Alavifar and Motamedi (2014), Aziz (2013), Love and Smith (2003), Interview.
• Frequent equipment breakdown • Shortages of skilled workers • Poor quality of materials • Conflicts between contractors and parties • Workers' absenteeism • Late-arrival of material/equipment • Contractor's lack of experience	Productivity (P)	Belgium, Egypt, India, Iran, Malaysia, New Zealand, Nigeria, Norway, Turkey, UK	Abbasi et al. (2020), Tahir et al. (2019), European Commission (2018), Karthik and Rao (2018), Zidane and Anderson (2018), Lessing et al. (2017), Moradi et al. (2017), Gascuene et al. (2014), Hickson and Ellis (2014), Aziz (2013), Desai and Bhatt (2013), Kazaz et al. (2012), Ameh and Osegbo (2011), Sullivan and Harris (1986), Interview.

A total of 27 independent variables are functions of five key delay factors. Design Error for example is associated with communication, consultant's experience, and technology usage.

The design process involves the input and contributions of experienced design professionals to create the engineering drawings as required. However, despite the preparations of the owner and the consultant, the design process of the construction projects is still characterized by colossal errors leading to schedule delay. "Design Error", a core problem that originates from the preconstruction stage, is a factor of failure in the construction stage that inhibits project progress, and causes design changes and rework, leading to construction delays and cost overruns in construction projects (Han et al., 2013; Rahman, 2018). Dosumu and Aigbavboa (2017) mentioned that design error accounts for 36% of construction costs. Fuade et al. (2017) further investigated the causes of design error in construction projects, and highlighted poor project management, lack of professionalism, and poor scope definition as influencing factors of design error. Shamsudeen and Obaju (2016) identified insufficient time and funds, lack of coordination, unclear scope of work, and designer's lack of experience as contributing factors of design error.

Habibi et al. (2018) commented that a common cause of delay and cost overruns in the construction phase is “Design Change”. Chang et al. (2011) explained that design change increases the time and cost of production. Redesign costs an average of 8.5% of the construction cost, and results in additional payments for contractors, rework, demolition, schedule delay, increased overhead expenses, and increased chances of conflict between owners and other stakeholders (Bassa et al., 2019). Han et al. (2013) mentioned that changes in requirements/specifications, unclear brief economic conditions, and omission of scope are items responsible for design change.

The effects of “Change Order” in the construction phase is also massive, as its occurrence greatly affects project performance by lowering quality, thereby affecting the time and cost (Khoso et al., 2019). Shrestha and Zeleke. (2018) explained that change order is a common problem in construction projects, and that it may increase a project's cost by 3.56%. 40% of schedule overruns are also caused by change order**s**. Gokulkarthi and Gowrishankar (2015) studied the impacts of change orders on construction projects, and highlighted changes of plans by an owner, owner financial difficulties, owner changes of schedule, and poorly defined project objectives as contributing factors of change orders.

Rezahoseini et al. (2019) stated that a large problem in the construction phase is “Rework”, as it affects almost all criteria of project success. Ajayi and Oyeyipo (2015) agreed that changes and defects during construction are major causes of rework. Anjum and Azam (2019) revealed that rework contributes 2% of construction cost. According to Abeku et al. (2016), poor monitoring, poor contractual arrangements, omissions, design/user change orders, defects and errors during construction, alterations to the initial design, and use of poor/inferior materials are leading causes of rework.

Venkatesh and Natarajan (2019) stated that poor “Productivity”, which is a major problem in the postconstruction phase, causes a project to lose up to 5% of the overall project value. Hickson and Ellis (2014) commented that the leading factors affecting construction productivity are lack of labor supervision, unrealistic scheduling and expectation of labor performance, shortages of experienced labors, lack of leadership skills, and delays in responding to requests for information. Gascuena et al. (2014) mentioned faulty work, overcrowded work areas, crew interference, lack of on-site cleanliness, equipment unavailability, and delays in inspection as factors affecting construction productivity.

The studies of construction delay are performed with various statistical approaches, such as the relative importance index, frequency analysis, average index, and linear regression to analyze key construction delay. Shahsavand (2018), for example, utilized the relative importance index to identify the major causes of delay in Iran, including change orders, underestimation of time and cost, and delays to equip and deliver sites. Gebrehiwet and Luo (2017) adopted the relative importance index to identify major delay factors in Ethiopia, including lack of quality materials, late design documents, late material delivery, late approvals, and poor management. Lessing et al. (2017) also utilized the relative importance index to rank key project-related and client-related factors. They found that short contract duration, type of project bidding and award, type of construction contract, and complexity of project design are top project-related factors, while defective materials provided by clients, change orders, cash flow problems, and late approval of the design documents by an owner are key client-related factors in the New Zealand construction industry. Durdyev et al. (2017) applied the relative importance index to summarize shortages of materials on-site, unrealistic project scheduling, late delivery of materials, shortages of skilled labor, and late payments by owners for completed work as the main causes of project delay in Cambodia. Desai and Bhatt (2013), Aziz (2013), Haseeb et al. (2011), and Faridi and El-Sayegh (2006) also utilized the relative importance index to highlight key construction delay factors in India, Egypt, Pakistan, and the UAE, respectively.

Kog (2017) utilized frequency analysis to identify key construction delay factors in Nigeria, and concluded that financing and payments for completed work, delays in material delivery, ineffective planning, and scheduling, and change orders are crucial construction delays. Owolabi et al. (2014), similarly, used the frequency index to pinpoint key construction delay factors in Nigeria, including insufficient client funds, design changes, lack of communication, and slow owner decision making. Samarah and Bekr (2016) identified management and supervision, design changes, and inadequate planning and control as the main delay factors in the Jordan construction industry utilizing the frequency analysis.

Jongo et al. (2019) employed the average index method to investigate variables affecting the performance and schedule of multi-unit residential building construction in Dar-es-Salam, Tanzania. They found that delays of completion time and payments, scope changes, design changes, unexpected ground conditions, and poor project management led to time overruns, while late payments, design errors, and scope changes affected cost. Akhund et al.

(2018) identified some construction delay factors utilizing the average index method, and highlighted financial difficulties faced by contractors, inadequate planning and scheduling, financial difficulties faced by clients, delays in decision making by clients, design errors, and frequent design changes as the key contributing factors of construction delay in Pakistan. Memon (2014) and Sweis et al. (2008) also adopted the average index to identify construction delay factors in Malaysia and Jordan, respectively.

Nenny and Kustamar (2019) used multiple linear regression analysis to unravel the leading cause of project delay and stated that the implementation method is crucial in reducing project delay. Mohammed and Suliman (2019) also adopted multiple linear regression analysis to summarize scope variation and delays in drawing preparation for a project as critical delay factors in Bahrain.

Considering the increase in sizes, and complexities of large-scale infrastructure projects in many developing countries, it is imperative to establish an improved understanding of the core factors that contribute to construction delays (Stephen et al. 2003). It is also necessary to narrow down those factors for a comprehensive understanding of the relationships among the core factors. To make it easy for project stakeholders to get acquainted with the key factors and assuage and subjugate the threat of schedule delay through effective decision. It is also important to conceptualize and comprehensively construct the relationships among key factors having established the hierarchical influence level of factors” to better understand and plan for construction scheduling and avoid delay.

“Decision making process is essential in managing successful organization (Anastasiu 2018). Oftentimes, there is a need to make decision every stage of the project (Szafranko, 2017). Various decision-making methods are applied to several diverse situations, therefore, management in construction projects entails series of decision. Strategy selection and strategy implementation are important phases decision making processes involved in construction projects. The four major approaches to a decision-making process can be inductive, deductive, development of a benefit matrix, and marginal analysis (Szafranko, 2015). These approaches are different from each other as they can be used separately, in a sequence, or in conjunction with each other (Jajak et al., 2015). For example, Samani et al. (2012) examined fuzzy systematic approach (i.e., Fuzz DEMATEL) to construction risk analysis, and concluded that country risk is the most important risk affecting the construction project in Iran. Seker et al. (2017) examined the application of fuzzy DEMATEL method for analyzing occupational risks on construction projects. Results show that Fuzzy DEMATEL method can evaluate causal factors of occupational hazards by a cause-effect diagram and improve certain measures on construction site. Erdogan et al. (2016) adopted the analytic hierarch process as a decision-making tool for construction management. It was discovered that the criteria “technical experience” is the leading criteria, which is associated with sub criteria: civil works, electrical, mechanical, landscaping and site works. Anastaciu (2018) investigated the decision-making process in construction project management using the ELECTRE I method. Results show that the construction industry in Romania is the most polluting due to the consistent usage of traditional technology. As a result, the European regulation will force the decision makers to find ways to perform without affecting the environment.

The intricacies involved in project scheme make the project system difficult. Factors embedded in the process of construction project implementation make the construction project very complex causing colossal challenges to the project control, thus debasing performance. Hierarchical listing of key factors and the cause-effect relationships among the key factors may not be adequate for the holistic investigation of construction delay. Having established the influence weight of these factors, it is also important to comprehensively explore the dynamics of these factors to establish the impact of these factors on the entire project schedule for effective decision and planning to significantly assuage the menace of construction project delay. According to Yu-jing (2012), system dynamics (SD) modelling is an effective way to improve performance through effective project control.

It has been steadily advocated by investigators to explore nonlinear and dynamic complexity issues involved in construction management. Maryani et al. (2015), for example, examined an SD approach for modelling construction accidents, while Liu et al. (2019) conducted a critical review and future trends on SD modelling for construction management research.

SD modelling involves the integration of methods, combining network analysis, fuzzy logic analysis, discrete event simulation, and agent-based simulation (Liu et al., 2019). It is used in examining the impact of contextual complicated condition in project planning and control, effectiveness and performance, strategic management, and sustainability (Liu et al., 2019). The importance of SD in advancing other decision-making methods in exploring relationships and dynamics of a system cannot be overemphasized, as it is the ground to establish impact of parameters on a set down standard, initiating effective decision to enhance better project performance”.

CHAPTER 3
RESEARCH METHOD

3.1 Overview

This “study develops a conceptual framework of construction delay, hypothesizing that construction delay is mainly caused by five key elements (or dependent variables), namely, Design Error, Design Change, Change Order, Rework, and Productivity. Each factor is associated with a number of independent variables. The five construction delay factors are used to develop the interview questions to collect the data for DEMATEL-SD analysis. The DEMATEL method is performed to examine the prominence of each key factor in construction-schedule delay. A causal loop diagram, based on the DEMATEL analysis results, is developed utilizing the SD modeling approach to depict the comprehensive relationships among key construction delay factors, and examine their impacts on project schedule. It is expected that the study results enhance the understanding of complex project systems for effective planning to avoid construction delays in the long term.

3.2 Research Flow

Research flow of this study is as shown in Figure 3.1. Literature review related to construction delay are conducted to examine relevant previous studies on key delay factors. Collected data from experts in the construction industry are then performed with the DEMATEL method to establish and develop the influence weights and a diagram of delay factors for SD modelling. The DEMATEL-SD model is established to examine the interrelationships among key delay factors through time. The developed DEMATEL-SD model is simulated and validated by experts and through the policy analysis to examine construction delay in the long term. The study results are concluded to enhance better understanding of construction project complexities and identify policies for effective decision making and planning, leading to the better construction project performance in terms of time.

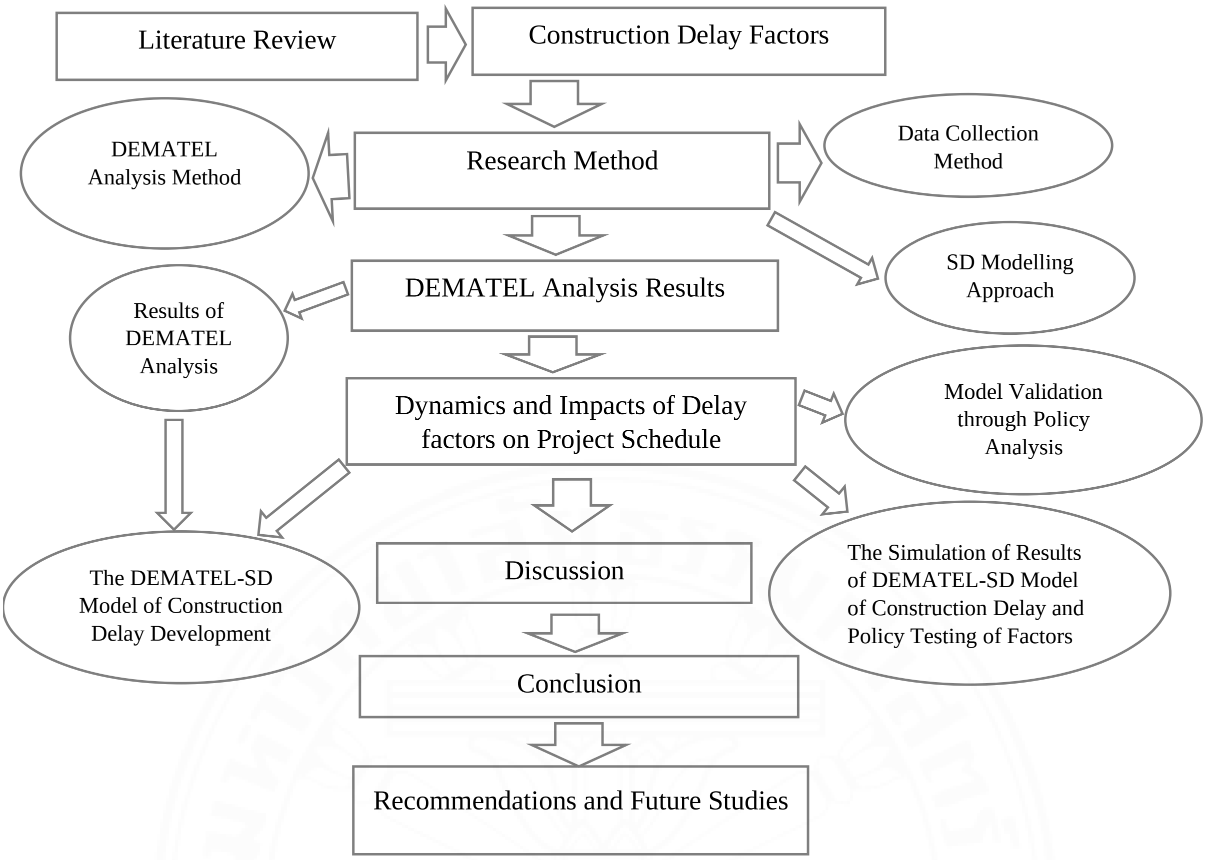

Figure 3.1 Research flow of this study

3.3 Data Collection Method and Respondents' Demography

The five key construction delay factors and their associated items are used to develop the interview questions to gather information for the DEMATEL-SD analysis. Sample size requirement, data collection methods (questionnaire and interview) and experiences of participants are crucial in data collection processes (Patel et al., 2003; Dennis, 2014). According to Dennis (2014), it is important to explore the experience of participants in practical investigation, as the resulting opinions have great impact on the study results.

In this study, experts are selected based on their experience in the Thai construction industry and are involved in solving construction delay issues. They have comprehensive knowledge about construction time lag, its responsible factors, how those responsible factors link with each other to result. The data are collated via binary comparison-oriented questionnaires, which were sent to experts electronically and in person. This collation system is seen as an effective and efficient instrument for gathering opinions from respondents (Hossain et al., 2020).

The introductory part of the interview requests respondents to provide their background information, including their current organization, position, and experience in the construction industry. The main part is designed to collect information about the degrees of influences among the five delay factors. The experts (respondents) are asked to rate the degree of influence (impact) of one factor on the other using the scale of 0 - 4, representing no influence to very high influence, respectively (Chaker et al., 2015; Kaushik & Somvir, 2015; Si et al., 2018; Hossain et al., 2020). This was done through binary comparison, where one factor is compared with another factor. An example of a question is "What is the degree of influence between the DE factor and the DC factor on the construction delay". A response of scale 4, or very high influence, depicts that DE factor has a very high influence on DC factor in causing construction delay. A response of scale 0, on the other hand, explains that DE factor has no influence on DC factor in causing construction delay. The designed questionnaire is reviewed by a group of qualified experts to validate its content before the final interviews.

The collected data from the interviews are performed with the DEMATEL analysis. Hossain et al. (2020) mentioned that DEMATEL analysis is not an approach premised on the sample size, but on the judgment of experts with reasonable years of experience in the industry of concern. The common sample sizes used in DEMATEL analysis ranges from 10-12 selected experts (Susanty et al., 2019; Morteza et al., 2014). In this study, 15 leading experts, working in the building construction companies in Bangkok and other provinces in Thailand, provide data for the analyses. This number of experts is considered adequate (Mohiuddin et al., 2017; Kumar & Dash, 2016; Tsai et al., 2016; Susanty et al., 2019). Among the 15 experts, 73% of them are males. They are contractors, consultants, and clients of building construction projects, representing 47%, 33%, and 20% of total responses, respectively. They work as engineers (40%), project managers (27%), architects (20%), and quantity surveyors (13%) in large-sized construction projects. Kanchana et al. (2015) mentioned that a large-sized construction project consists of at least 100 workers with a capital investment of at least 100 million baht. More than 80% of respondents have at least 10-year working experiences in large-sized building construction and their current organizations. They are also involved in various decision makings related to construction delays.

Respondents' years of working experiences and their roles in the construction projects prove their appropriateness in providing the data for the DEMATEL-SD analysis. The diagrammatic representations of the respondents' demography are depicted in Figures 3.1-3.4.

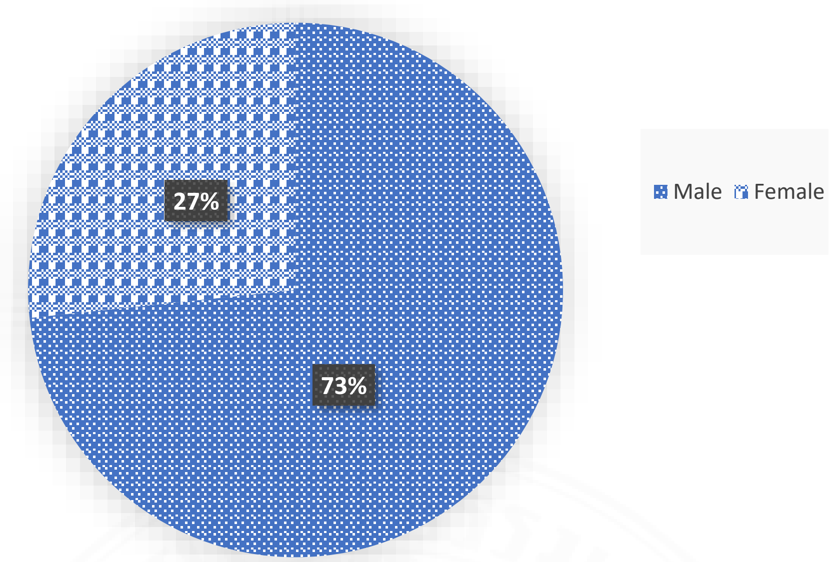

Figure 3.2 Gender of the repondents

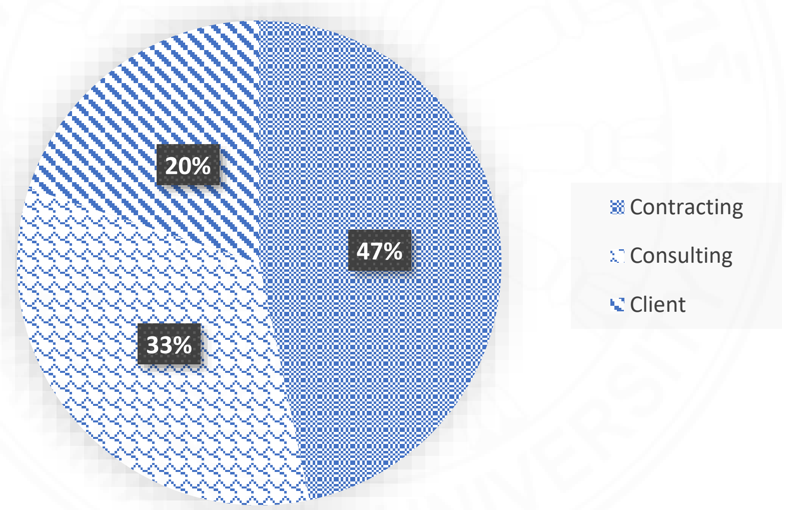

Figure 3.3 Type of organization of the respondents

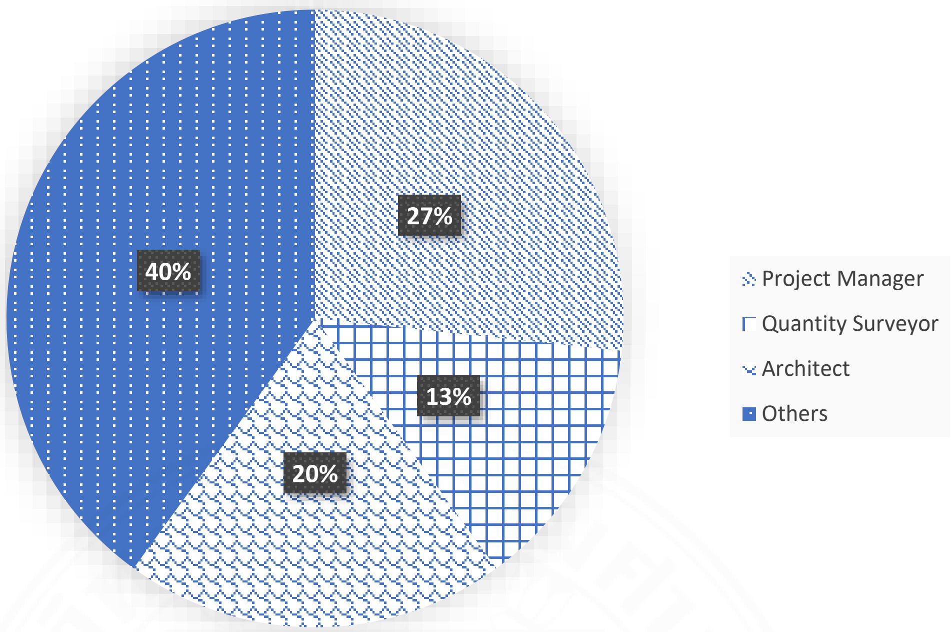

Figure 3.4 Job tittle of the respondents

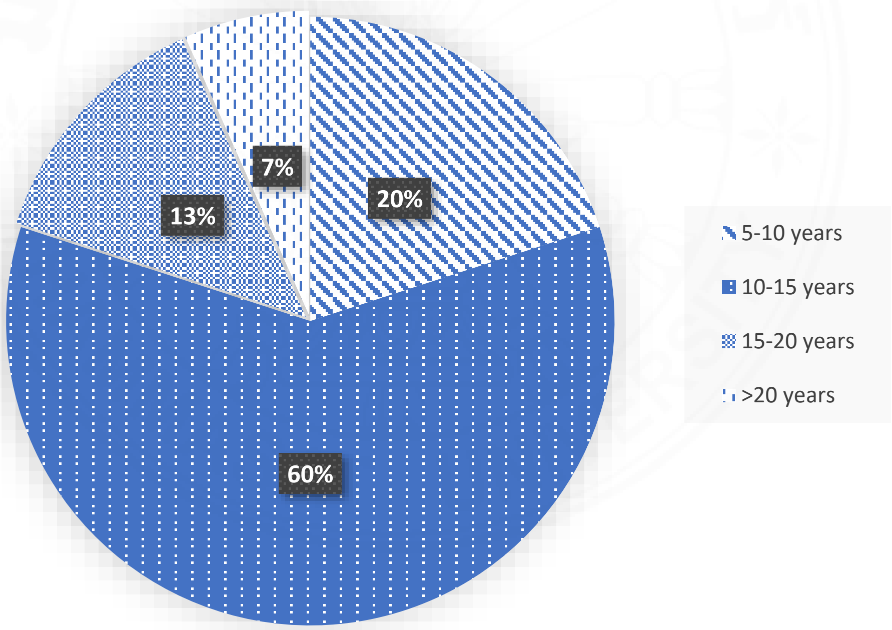

Figure 3.5 Working experience of the respondents

It is also important to check the internal consistency of the collated data to validate the reliability of the judgmental opinion of the experts (Mohiuddin et al., 2017). This research utilizes the Cronbach's alpha value to check the internal consistency of the data collected (SAS, 2007). Cronbach's alpha is not a consistency check system restricted to be performed on a certain number of sample size. Rather, it has been performed on various number of data set by scholars. This depicts the fact that Cronbach's alpha as a method of consistent check is an open interval or annulus for a significant number of data size or survey questions (Das & Emuze, 2017). It is, therefore, noteworthy that 15 opinions are enough to perform Cronbach's alpha analysis, as similar sample sizes have been used by extant researchers to achieve excellent alpha values (Bujang et al., 2018; Tan et al., 2015 Bonet & Wright, 2014; Hertzog, 2008; Yurdugul, 2008; Ercan et al., 2007; Kistner & Muller, 2004; Bonett, 2002). Hertzog (2008), for example, mentioned that samples ranging from 10-40 per group are evaluated for their adequacy in providing estimates precise enough to meet a variety of possible aims. Ercan et al. (2007) commented that sample size is not important for coefficient alpha, and estimates could be stable even with very small sample sizes. Bujang et al. (2018) stated that for a single coefficient alpha test, the approach by assuming the Cronbach's alpha coefficient equals to zero in the null hypothesis will yield a smaller sample size of less than 30 to achieve a minimum desired effect size of 0.7. Yurdugül (2008), similarly, found that for an unbiased estimate of reliability using coefficient alpha, a sample size of up to 30 is sufficient with a large first eigenvalue. Tan et al. (2015) examined the construct validity of intention to adopt pharmacy value-added services and utilized the Cronbach's alpha with sample size of 25 to measure the scale reliability of the study. The results in this study revealed that the judgements of the experts used in the DEMATEL analysis are highly reliable with Cronbach's alpha of 0.939, which is greater than a minimum acceptable value of 0.7 (SAS, 2007)".

3.4 Overview of DEMATEL Analysis

Decision-Making Trial and Evaluation Laboratory "(DEMATEL) analysis was originally developed to resolve complicated and intertwined problematic groups using a mixture of matrices (Kakha et al., 2019; Shieh et al., 2010; Wu et al., 2010). It is effective to evaluate and formulate the cause-and-effect relationships in structured models and is an effective method for designers and decision makers, especially in the management field (Kaushik & Somvir, 2015). It has been widely applied in many areas, such as airline safety management, emergency management, web advertisement, enterprise resource planning, hospital service quality, mobile banking system service, and the auto spare parts industry (Wu & Tsai, 2011; Shieh et al., 2010; Wu et al., 2010). For example, Oke and Onyegiri (2016) applied the DEMATEL technique as a decision tool for an effective safety management system in aviation transport and concluded that safety culture and regulation have the highest positive impact on safety management system. Liou et al. (2008), similarly built an effective safety management system for airlines using the DEMATEL method and concluded that strategy and policy plays the most important role in an effective safety management system. Li et al. (2014) used the DEMATEL method to identify critical success elements in emergency management. It is concluded that if the pertinent critical success factors are improved, the whole emergency management can be improved. Wei et al. (2010) utilized the DEMATEL results in the structural equation modelling to develop the causal model of web-advertising effects and concluded that pertinent factors affecting web-advertising assist managers in making strategic marketing plans. Lee et al. (2020) studied a decision-making framework for evaluating enterprise resource planning systems in a high-tech industry. It is concluded that an integrated DEMATEL system helps firms evaluate enterprise resource planning systems effectively by collecting experts' opinions in an uncertain environment. Shieh et al. (2010) identified key success factors of hospital service quality and concluded that trusted medical staff should provide professional competence of health care to patients for satisfaction to be increased. Rad et al. (2019) applied the DEMATEL method in transaction authentication of mobile banking. It is concluded that the use of mobile systems in authentication methods, authentication with fingerprint, and smart card are considered as the causative group, while authentication with a bank card, biometric authentication and disposable codes are among the effective group. Wu and Tsai (2011) investigated the causal relations among the criteria in auto spare parts industry and discovered that suppliers need to pay attention to percent of research and development, flexibility and responsiveness, and geographical location to improve performance.

DEMATEL analysis method, similar to other methods, such as Analytical Hierarchical Process (AHP), Grey Relational Analysis (GRA), Vise Kriterijumska Optimizacija Kompromisno Resenje (VIKOR), and Elimination Et Coix Traduisant la REalite (ELECTRE), is a multiple criteria decision-making method (Si et al., 2018). It is applied in this research study due to a number of distinct advantages as follows:

- It effectively analyzes the mutual influences (both direct and indirect effects) among different factors and is easy to understand the complicated cause and effect relationships in the decision-making problem.
- It can establish the interrelationships among variables and enable the decision makers to comprehend which elements have mutual influences on one another.
- It can be used not only to determine the ranking of alternatives, but also to identify critical evaluation criteria, and measure weights of evaluation criteria (Si et al., 2018).

Though a number of advantages, this method has its own limitations.

- It determines the ranking of alternatives based on interdependent relationships among them; other criteria are not incorporated in the decision-making problem.
- The relative weights of experts are not considered in aggregating personal judgements of experts into group assessments.
- It cannot consider the aspiration level of alternatives as in the GRA and VIKOR methods or obtain partial ranking orders of alternatives as in the ELECTRE approach" (Si et al., 2018).

3.5 Steps of the DEMATEL Analysis

In this study, a seven-step of DEMATEL is proposed (Abdullah et al., 2019; Kakha et al., 2019; Kaushik & Somvir, 2015; Amiri et al., 2011; Shieh et al., 2010).

- Step 1: Compute direct-relation (average) matrix A: To assess the relationships between n factors $F = \{F_1, F_2, \ldots, F_n\}$ in a system, it is supposed that H respondents/experts in a decision group $E = \{E_1, E_2, \ldots E_H\}$ are asked to evaluate the direct influence that factor F_i has on F_j using an integer score ranging from 0 to 4, representing "no influence" to "very high influence, respectively. Then, the individual direct-influence matrix $Z^k = [z_{ij}^k]_{nxn}$ provided by the k^{th} expert can be formed, where all principal diagonal elements are equal to zero, and z_{ij}^k represents the judgment of decision-maker E_k on the degree to which factor F_i affects factor F_j for $i = j$. $Z_k = [z_{ij}^k]_{nxn}$ is an (n x n) non-negative matrix, k is the number of respondents, with $1 \leq k \leq H$ i.e., $k \in [1, H]$, and n is the number of factors. Thus, $Z^1, Z^2, Z^3, \ldots, Z^H$ are the matrices from H respondents. The (n x n) average matrix $A = [a_{ij}]$ for all expert opinions can be computed by averaging the scores of the H experts, as shown in Equation 3.1.

$$A = [a_{ij}] = \frac{1}{H}\sum_{k=1}^{H} z_{ij}^k \quad (3.1)$$

The average matrix $A = [a_{ij}]_{nxn}$, which is also called the original average matrix, shows the direct effects that a factor exerts on, and receives from, other factors.

Furthermore, the causal effects between each pair of factors in a system can be mapped out by drawing an influence map.

- Step 2: Normalize direct-relation matrix A. By normalizing the average matrix A, normalized direct-relation matrix D can be obtained in which the value of each element in matrix D is between 0 and 1 (see Equations, 3.2 and 3.3), where S is the maximum value among the sum of direct relation matrix A values in each row.

$$S = Max\left[max_{1\le i\le n}\sum_{j=1}^{n} a_{ij}, max_{1\le j\le n}\sum_{i=1}^{n} a_{ij}\right] \quad (3.2)$$

$$D = \frac{A}{S} \quad (3.3)$$

- Step 3: Compute total-relation matrix T. Total-relation matrix T is an (n x n) matrix, and is defined by Eq. 3.4, where I is the identity matrix.

$$T = \left[t_{ij}\right]_{nxn} = D(I - D)^{-1} \quad (3.4)$$

- Step 4: Calculate the sum of rows (R) and the sum of columns (C). In total-relation matrix T, the sum of rows and the sum of columns are expressed by vectors R and C, respectively, where vectors R and C are separately expressed as the sum of rows and the sum of columns from total-relation matrix $T = \left[t_{ij}\right]_{nxn}$, respectively (see Equations 3.5 and 3.6).

$$R = \left[\left(\sum_{j=1}^{n} t_{ij}\right)\right]_{n\times 1} = [t_i]_{nx1} \quad (3.5)$$

$$C = \left[\left(\sum_{i=1}^{n} t_{ij}\right)\right]_{1\times n} = \left[t_j\right]_{1xn} \quad (3.6)$$

- Step 5: Calculate the prominence and the total-relation matrix. The vector $(R_i + C_j)$ is called the prominence, which indicates the degree of influence of each factor.

Vector $(R_i - C_j)$ is called the relation vector, which may divide factors into cause-and-effect groups. If the relation vector is positive, then factor i tends to fall under the cause group. In contrast, if the relation vector is negative, then factor i tends to fall under the effect (receiver/result) group.

- Step 6: Select a threshold value (α) to obtain the digraph. Since matrix T provides information on how one factor affects another, it is necessary for a decision maker to set up a threshold value to filter out some insignificant effects. Only the effects greater than the threshold value are selected and shown on the digraph. In this study, the threshold value α is set up by computing the average of the elements in matrix T using Equation 3.7.

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[t_{ij}\right]}{N} \quad (3.7)$$

- Step 7: Construct a cause-and-effect relationship diagram. The causal diagram can be obtained by mapping all coordinates $(R_i + C_i,\ R_i - C_i)$ onto two planes, which may provide some insight when making decisions. The causal diagram visualizes the importance and classification of all factors".

3.6 System Dynamics Modelling Approach

The causal diagram achieved from the DEMATEL analysis results is used as a basis for SD model development. System dynamics (SD) modelling is a field created at Massachusetts Institute of Technology "(MIT) by computer pioneer, Jay Forrester, in mid 1950s for modelling and analyzing the behavior of complex systems in industrial context (Boateng et al., 2012). It was designed to help decision-makers learn about the structures and dynamics of complex systems, design high leverage policies for sustained improvement, and speed up successful implementation and change. It is a systematic thinking that enhances communication of information of high level of complexity to be disseminated into simplified circular loop feedback structure. It is based on the concept of causal loop diagram and is effective to model processes that involve changes over time, and feedback concept (the transmission and receipt of information) (Ogunlana, 2003).

Clear understanding of how the parts in a system interact with each another, and how a change in one variable affects the other variables over time is the core of SD modelling. Each causal link is assigned a polarity, either positive (+) or negative (-), to indicate how a variable impact or is impacted by the other over time (Sterman, 2000). Kim (1999) explained that a positive (+) link indicates that as one variable changes, the next variable changes in the same direction, or $\frac{\partial y}{\partial x} > 0$. A negative (-) link, on the other hand, indicates that as one variable changes, the other changes in the opposite direction, or $\frac{\partial y}{\partial x} < 0$.

A causal loop can either be reinforcing or balancing based on the number of negative (-) sign, if there are no negative (-) sign, or an even number of negative (-) signs, then the loop is reinforcing. Contrary, if there is an odd number of negative (-) signs, then the loop is balancing (Kim, 1999). Another central concept of the SD approach is the stock-flow diagram. It is a representation of significant or insignificant accumulations within the system. On the other hand, flows that signify the rates of changes in the system are represented by inflows (which increase the level of the stock) or outflows (which reduce the stock level). The mathematical relationship between stocks and flows is given in Equation 3.8.

$$Stock(t) = \int_{to}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_o) \quad (3.8)$$

Where t_o is the initial time, $Stock(t_o)$ represents the stock level at the initial time, s indicates the change in the time variable between the initial time and the current time, and $Inflow(s)$ and $Outflow(s)$ represent the information going into and going out of the stock at time s, respectively (Chaker et al., 2015).

The initial stock does not have to be positive as it may be negative, null, or positive (Chaker et al., 2015). A net flow of stock, also known as the derivative of the stock, is defined as some function of variables and constants. Since most of the system is premised on feedback structure, the net flow will depend on the stock. Therefore, a net flow of a stock is represented by Equation 3.9

$$Net\ flow = \frac{dS}{dt} = f(S, t) \quad (3.9)$$

Where S is an amount of quantity in the stock, t is time, and $f(S, t)$ is a function that depends on S and t (Choopojcharoen & Magzari, 2012).

In this study, the DEMATEL analysis results, which is a strong decision-making method, is used as input and pathways to the SD model development. This study combines the advantages of two effective methods (DEMATEL and SD) to overcome shortcomings. The study establishes the digraph of factors through a well-formulated total-relation matrix based on experts' judgement, constructs the causal loop diagram, and shows the causal relationships among the influencing factors of construction delay, as well as the influence weights of factors, and examines the dynamics of the delay factors and their impacts on project schedule". The variables in the developed DEMATEL-SD model are prepared for several simulation runs with the default values of parameters used to start the simulation runs. The exogenous variables are modeled to initiate the encapsulating endogenous variables, which will be varied with the improvement of factors. These changes, with respect to time, result in different project completion time. Consistent minimization key factors, which signify steady improvement, improves productivity, and in turn, reduces the project delivery time and delay.

CHAPTER 4
DEMATEL ANALYSIS RESULTS

4.1 Overview

This chapter showcases the DEMATEL analysis of the construction delay factors. The collected data from construction experts are analyzed with DEMATEL method using the MATLAB 2019 software. The analysis results are explained in this chapter.

4.2 Experts Information

The respondents, comprising of reasonable numbers of leading experts from contracting and consulting firms, working as engineers, project managers, architects, and surveyors give their judgmental opinions on the interactions among factors via pair-wise comparison. These experts are highly experienced and are also active participants and superintendents of large-sized construction projects in Bangkok and other provinces in Thailand. Their opinions and pair-wise comparison scores are used in the DEMATEL analysis (see more details of the experts in Appendix A).

Each expert answered five pertinent questions using a scale of 0-4. The questions and answers that arise from the interviews initiate a 5 x 5 (square) matrix system. The questions are given as; (1) what are the influences of DE on DE, DC, CO, R, and P, respectively, (2) what are the influences of DC on DE, DC, CO, R, and P, respectively, (3) what are the influences of CO on DE, DC, CO, R, and P, respectively, (4) what are the influences of R on DE, DC, CO, R, and P, respectively, and (5) what are the influences of P on DE, DC, CO, R, and P, respectively. By default, the influence of a factor on itself is zero. For example, the influence of DE on DE is 0 (i.e., no influence).

The tabular representation of the questions is as shown in Table 4.1. For an example, Respondent #1 (R1) believes that DE has low influence on DC in causing construction delay, then the score of 2 is given from DE to DC. This respondent, however, believes that DC has a very high influence on P (the score of 4 is given from DC to P).

Table 4.1 Results of pair-wise comparisons of each expert

Respondent #1 (R1)

	DE	DC	CO	R	P
DE	0	2	4	3	3
DC	2	0	2	1	4

CO	2	2	0	3	1
R	4	2	3	0	3
P	1	1	3	3	0

Respondent #2 (R2)

	DE	DC	CO	R	P
DE	0	1	2	1	2
DC	1	0	1	2	2
CO	2	2	0	1	3
R	1	2	1	0	2
P	3	2	1	1	0

Respondent #3 (R3)

	DE	DC	CO	R	P
DE	0	3	2	2	1
DC	3	0	2	1	3
CO	1	2	0	3	2
R	1	3	3	0	2
P	2	1	3	3	0

Respondent #4 (R4)

	DE	DC	CO	R	P
DE	0	4	4	4	4
DC	4	0	4	4	4
CO	4	4	0	4	4
R	4	4	4	0	4
P	4	4	4	4	0

Respondent #5 (R5)

	DE	DC	CO	R	P
DE	0	3	2	3	2
DC	3	0	3	3	3

CO	3	2	0	3	3
R	3	2	3	0	3
P	3	3	3	3	0

Respondent #6 (R6)

	DE	DC	CO	R	P
DE	0	2	3	2	2
DC	2	0	2	3	2
CO	2	2	0	2	2
R	2	2	2	0	2
P	2	2	2	2	0

Respondent #7 (R7)

	DE	DC	CO	R	P
DE	0	3	3	4	3
DC	2	0	2	2	2
CO	2	2	0	2	2
R	2	2	2	0	2
P	2	2	3	2	0

Respondent #8 (R8)

	DE	DC	CO	R	P
DE	0	2	2	2	2
DC	2	0	2	2	2
CO	2	2	0	2	2
R	2	2	2	0	2
P	2	2	2	2	0

Respondent #9 (R9)

	DE	DC	CO	R	P
DE	0	2	2	3	3
DC	2	0	3	3	3

CO	3	2	0	2	3
R	3	3	2	0	3
P	2	2	3	3	0

Respondent #10 (R10)

	DE	DC	CO	R	P
DE	0	2	1	1	1
DC	2	0	1	1	1
CO	1	2	0	2	2
R	2	2	2	0	2
P	2	2	2	2	0

Respondent #11 (R11)

	DE	DC	CO	R	P
DE	0	2	3	2	3
DC	2	0	3	2	2
CO	3	2	0	2	3
R	3	2	2	0	2
P	3	3	2	2	0

Respondent #12 (R12)

	DE	DC	CO	R	P
DE	0	3	2	3	2
DC	3	0	2	3	3
CO	2	3	0	2	3
R	3	3	3	0	2
P	3	3	3	3	0

Respondent #13 (R13)

	DE	DC	CO	R	P
DE	0	2	1	1	2
DC	2	0	2	2	1

CO	2	2	0	2	2
R	1	1	2	0	2
P	2	2	2	2	0

Respondent #14 (R14)

	DE	DC	CO	R	P
DE	0	1	2	3	1
DC	3	0	1	2	2
CO	2	3	0	1	3
R	4	2	2	0	3
P	1	3	2	3	0

Respondent #15 (R15)

	DE	DC	CO	R	P
DE	0	2	2	2	2
DC	2	0	2	2	1
CO	3	1	0	3	3
R	2	3	2	0	1
P	2	2	2	2	0

The scores of the 15 experts are used in the analysis. The results are as shown in the next section.

4.3 DEMATEL Analysis Results

4.3.1 Step 1 Results

Step 1 computes the direct-relation matrix A. The direct-relation matrix A of all 15 experts was calculated, as shown in Table 4.2. In matrix A, the element z_{ij}^{k} denotes the impact that factor i has on factor j according to expert k (see Equation 3.1 in Chapter 3). For example, the summation of values in the "DE" row is calculated as 0.0000 + 2.2667 + 2.3333 + 2.4000 + 2.2000 = 92000. The sum value (S) is then the maximum sum value among five rows, including 9.2000, 8.7333, 9.2667, 9.4666, and 9.1334, thus achieving 9.4666 (see Equation 3.2 in Chapter 3).

Table 4.2 Matrix A calculation

A						Sum
	DE	DC	CO	R	P	
DE	0.0000	2.2667	2.3333	2.4000	2.2000	9.2000
DC	2.3333	0.0000	2.0667	2.2000	2.1333	8.7333
CO	2.2667	2.2000	0.0000	2.2667	2.5333	9.2667
R	2.4667	2.3333	2.3333	0.0000	2.3333	9.4666
P	2.1333	2.2667	2.2667	2.4667	0.0000	9.1334
S						9.4666

4.3.2 Step 2 Results

The normalized initial direct-relation matrix D is constructed (see Equation 3.3 in chapter 3.3) by dividing A values by S value (see Table 4.2). The results are as shown in Table 4.3. For instance, by dividing the A value of 2.2667 (from DE to DC in Table 4.2) by S value of 9.4666, the value of 0.2394 is achieved (see Table 4.3 from DE to DC).

Table 4.3 Matrix D calculation

D					
	DE	DC	CO	R	P
DE	0.0000	0.2394	0.2465	0.2535	0.2324
DC	0.2465	0.0000	0.2183	0.2324	0.2254
CO	0.2394	0.2324	0.0000	0.2394	0.2676
R	0.2606	0.2465	0.2465	0.0000	0.2465
P	0.2254	0.2254	0.2394	0.2606	0.0000

4.3.3 Step 3 Results

Total-relation matrix T is calculated, as described in Table 4.4 (see Equation 3.4 in Chapter 3). Multiplying Matrix D by the inverse of the difference between the Identity matrix (I) and Matrix D results in Table 4.4.

Table 4.4 Matrix T and the sum of rows (R) and sum of columns (C) calculation

T					
	DE	DC	CO	R	P
DE	5.4310	5.4966	5.5346	5.6969	5.6188
DC	5.4031	5.0831	5.2944	5.4551	5.3883
CO	5.6525	5.5199	5.3652	5.7173	5.6705
R	5.7624	5.6223	5.6571	5.6210	5.7525
P	5.5223	5.3969	5.4389	5.6078	5.3376

4.3.4 Step 4 Results

The sums of rows (R) and columns (C) are obtained from a total-relation matrix T (see Table 4.5, and Equations 3.5 and 3.6 in Chapter 3). The sum of "DE" row of 27.7779 is, for example the sum value of 5.4310, 5.4966, 5.5346, 5.6969, and 5.6188 in Table 4.4. The sum of "DE" column of 27.7713 is, on the other hand, achieved by the summation of 5.4310, 5.4031, 5.6525, 5.7624, and 5.5223 (see Table 4.4).

Table 4.5 Ri, Ci, (Ri+Ci) and (Ri-Ci) calculation

Factor	Ri	Ci	Prominence (Ri + Ci)	Relation (Ri - Ci)
DE	27.7779	27.7713	55.5492	0.0066
DC	26.6240	27.1188	53.7428	-0.4948
CO	27.9254	27.2902	55.2156	0.6352
R	28.4153	28.0981	56.5134	0.3172
P	27.3035	27.7677	55.0712	-0.4642

4.3.5 Step 5 Results

The vectors (Ri+Ci) and (Ri-Ci) are calculated by summing each Ri with each Ci in the same row (see Table 4.5). For example, the (Ri + Ci) value of the DE row is 27.7779 + 27.7713 = 55.5492. The (Ri-Ci) value, on the other hand, is 27.7779-27.7713 = 0.0066.

4.3.6 Step 6 Results

In this study, the threshold value (α) is calculated using Equation 3.7 in Chapter 3 to trash out insignificant effects and bias. All T values in Table 4.4 are summed and divided by the total number of data (which is 25). The α value is then 5.5218. According to Rezahoseini et al. (2019), it is important to form Matrix F by setting element T_{ij} in Table 4.4 that is equal or larger than the threshold (α) of matrix T to 1, and element T_{ij} in Table 4.4 that is less than threshold (α) of matrix T to 0. For example, the T value from DE to DE in Table 4.4 is 5.4310, which is lower than the α value of 5.5218. This brings the F value from DE to DE in Table 4.6 to 0. On the other hand, the T value from DE to CO in Table 4.4 of 5.5346 bring its F value to 1, as it is higher than the α value (see Table 4.6).

Table 4.6 Matrix F (for $\alpha = 5.5218$)

F					
	DE	DC	CO	R	P
DE	0	0	1	1	1
DC	0	0	0	0	0
CO	1	0	0	1	1
R	1	1	1	1	1
P	1	0	0	1	0

Matrix F (Table 4.6) is used to construct the DEMATEL digraph (see Figure 4.1). For example, the relationship between DE and CO is 1, and the relationship between CO and DE is also 1. These relationships are represented by arrows pointing from DE to CO, and from CO to DE (see Figure. 4.1). On the other hand, the relationship between R and DC is 1, while the relationship between DC and R is 0. These, therefore, result in an arrow pointing from R to DC (see Figure. 4.1).

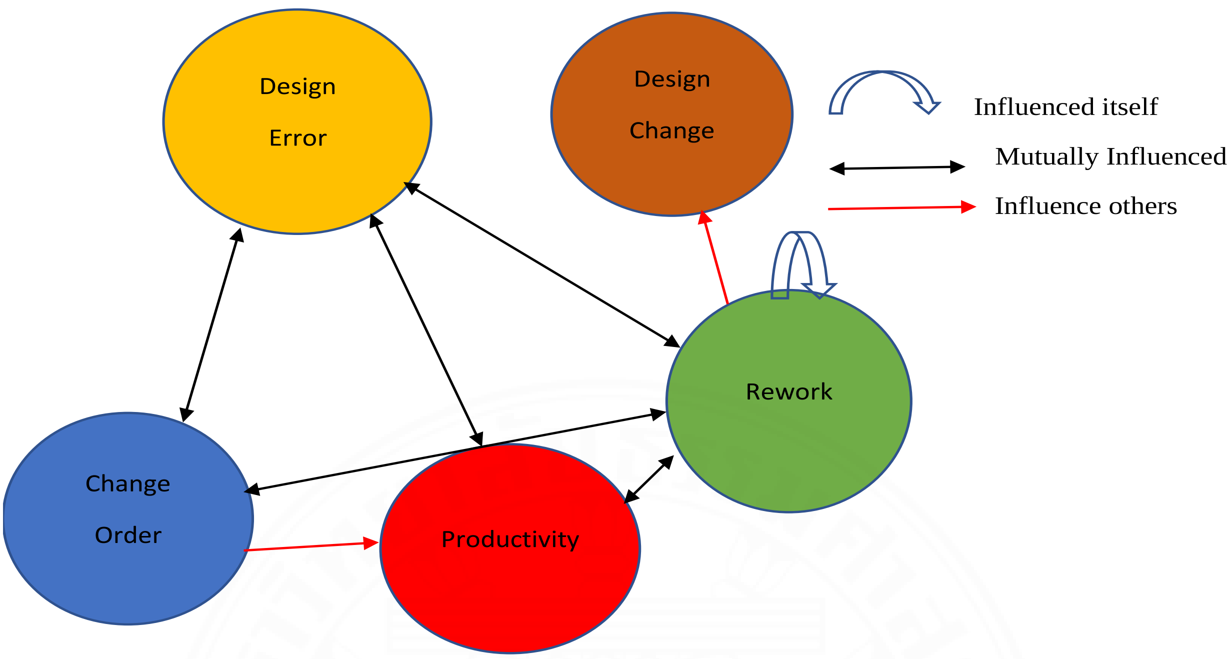

Figure 4.1 Diagraph of construction delay

The DEMATEL digraph shows that the Design Error (DE) factor has mutual influences with the Change Order (CO), Rework (R), and Productivity (P) factors, while the Design Change (DC) factor is influenced by the Rework (R). Rework (R) has mutual influence with the Design Error (DE), Change Order (CO), and Productivity (P) factors, and also influences itself.

4.3.7 Step 7 Results

The cause-effect diagram is drawn using the coordinates (Ri + Ci) and (Ri – Ci) in Table 4.5. The values of (Ri + Ci) stand for the degree of influence among factors, while (Ri-Ci) indicates the relations among factors. Positive values are grouped as cause factors, while the negative values are effect factors (Abdullah et al., 2019).

The (Ri + Ci) and (Ri – Ci) values in Table 4.5 are plotted in the cause-and-effect diagram (see Figure 4.2). It shows that the Rework (R) factor is the most influencing factor, while the Design Change (DC) factor is the least influencing factor. The Rework (R), Design Error (DE), and Change Order (CO) factors are grouped as the cause group as their (Ri – Ci) values are positive. In contrast, the Productivity (P) and Design Change (DC) factors are categorized under the effect group as their (Ri – Ci) values are negative (see Table 4.7).

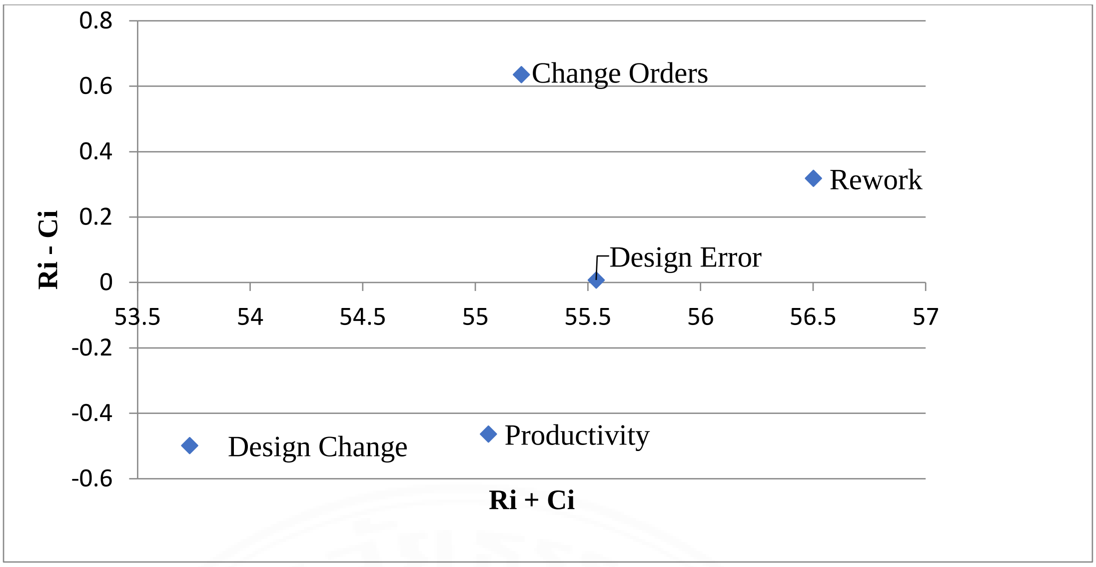

Figure 4.2 Cause and effect diagram of construction delay

Table 4.7 Order of influence of construction delay factors

Factors	Prominence (Ri+Ci)	Rank of factors	Relation (Ri-Ci)	Cause/Effect Group
Rework (R)	56.5134	1	Positive	Cause
Design Error (DE)	55.5492	2	Positive	Cause
Change Order (CO)	55.2156	3	Positive	Cause
Productivity (P)	55.0712	4	Negative	Effect
Design Change (DC)	53.7428	5	Negative	Effect

The total degree to which a factor is influenced by the other factor (i.e., the influence weight) is established by dividing each prominence value (see Table 4.7) to the sum of all prominence values, which is 56.5134 + 55.5492 + 55.2156 + 55.0712 + 53.7428 = 276.0922. The importance weight of the R factor is, for example $\frac{56.5134}{276.0922} \times 100 = 20.4690\%$ (see Table 4.8)

Table 4.8 Total degree to which a factor is influenced by the other factors

Rank	Factor	Value (%)
1	Rework (R)	20.4690
2	Design Error (DE)	20.1198
3	Change Order (CO)	19.9990
4	Productivity (P)	19.9467
5	Design Change (DC)	19.4655

The results show that the R factor is the most influencing factor of construction project delay, followed by the DE, CO, P, and DC factors, respectively. The summary of the DEMATEL analysis results is as shown in Figure 4.3.

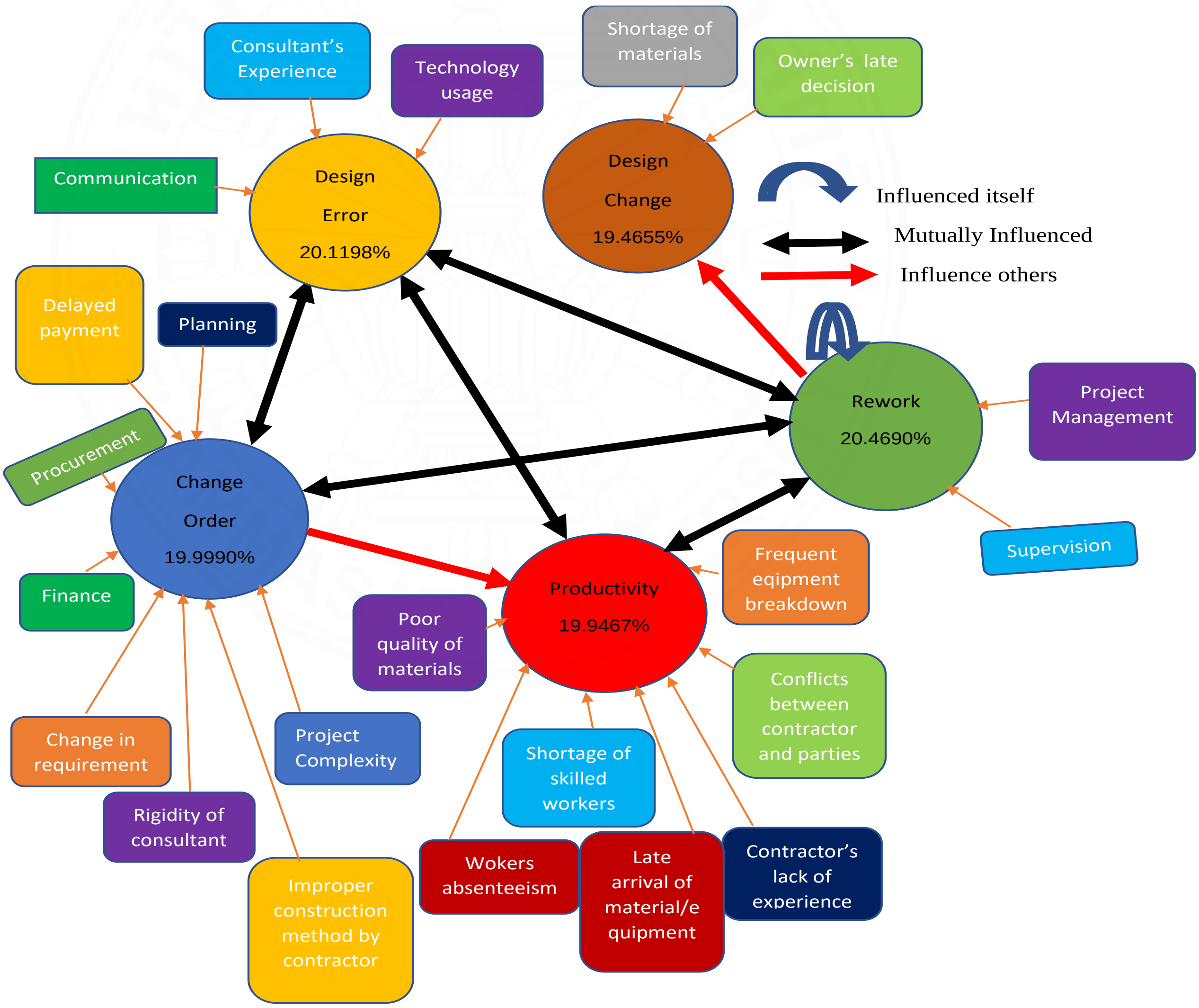

Figure 4.3 Cause and effect diagram of construction delay factors with their influence

Comprehensive relationships among the five key delay factors and their associated sub criteria are established using the causal loop diagram of system dynamics modelling. It is important to show the links between the factors under consideration (i.e., how the factors interact with each other) for better comprehension of the complexities involved in construction projects to enhance effective decision in successful project delivery. Details are in the next chapter.

CHAPTER 5
DYNAMICS OF THE CONTROLLING FACTORS OF DELAY AND THEIR IMPACTS ON PROJECT SCHEDULE

5.1 Overview

This chapter presents the development of the “dynamic model of construction delay factor. The summary of DEMATEL analysis results, displayed in Chapter 4, showcases the relationships among the five key delay factors with their associated sub-criteria. Based on this, the dynamics of those factors will be explored in this chapter to investigate the impacts of the pertinent factors on project schedule, thus enhancing better project performance in terms of time. For example, the changes in the magnitude of design errors at the early stage of construction could have significant impacts on the entire project schedule. Designers' experience, technology advancement, and effective communication, which are associated variables of the Design Error factor, are used to examine, compute, and control the impact of design errors at necessary instances of the project execution. On the other hand, project management and supervision, which are the associated sub- criteria of the Rework factor, in connection with the impacting conditions of the other key factors, are extensively considered to examine the rework flow throughout the entire project process. Complex relationships among the key construction delay factors are depicted through the causal loop diagram, which is used in the DEMATEL-SD model development.

5.2 Causal Loop Diagram of Construction Delay Factors

The relationships among the delay factors established through DEMATEL analysis are comprehensively explored through a causal loop diagram to examine how dependent and independent variables relate with each other, see Figure 5.1. For example, Rework influences Design Change according to the DEMATEL results. More reworks may result in shortage of materials (an item in the Design Change factor) (Bassa et al., 2019). Rework also has a relationship with the productivity factor. Less supervision (an item in the Rework factor) may result in high conflict between personnel (an item in the productivity factor). Figure 5.1 explicitly explains and expands all the DEMATEL-established interactions. Four experts working in leading construction companies in Thailand took part in the model validation process. These number of experts are adequate for the validation process (Yusoff, 2019). Some of the experts participated in the pairwise comparison of the delay factors for DEMATEL analysis. These experts were taken through the conceptual model, detailing the establishment of the conceptual model from the DEMATEL resulting cause-and-effect diagram, and the need for a comprehensive and realistic causal loop diagram to achieve a robust and reliable DEMATEL-SD system to investigate the dynamics and impact of delay factors on project schedule to come up with effective policies that would help subjugate project delay in the long term. The suggestion for re-arrangement of the subsystems to include pertinent endogenous variables (like overtime and fatigue among others) was addressed. The model was, thereafter, adjusted as recommended, thereby paving way for their approval.

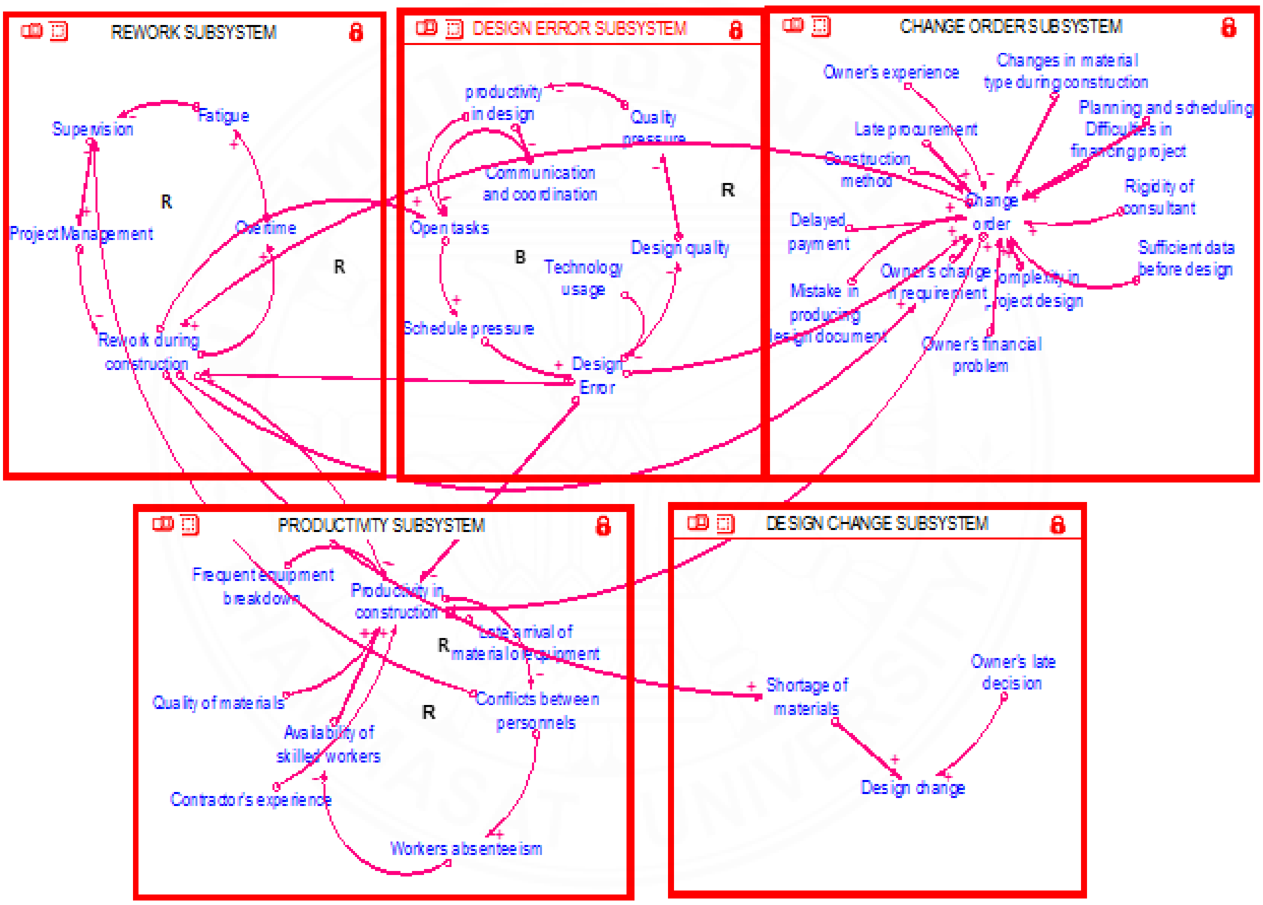

Figure 5.1 Causal loop diagram of construction delay

The causal loop diagram consists of a number of positive and negative links and loops. In the Rework subsystem, for example, poor project management could result in more rework during construction. This represents a negative (-) link between the 'project management' and 'rework during construction' items. More reworks require overtime work, leading to fatigue. These represent positive (+) links between the 'rework during construction' and 'overtime' items, and the ‘overtime’ and ‘fatigue’ items. With high fatigue, less supervision is provided (a negative link), resulting in poor project management (a positive link). These close a reinforcing loop (R) among the ‘poor project management’, ‘rework during construction’, ‘overtime’, ‘fatigue’, and ‘supervision’ items in the Rework subsystem.

Rework factor influences Design Error, Change Order, Productivity, and Design Change factors (see Figure 4.4 in Chapter 4). Rework during construction adds more open tasks to be completed (a positive link), leading to high schedule pressure (a positive link) and design errors (a positive link). Design error then forces change order (a positive link) resulting in more rework in the construction (a positive link). These, thus, close a reinforcing loop (R) among the ‘rework during construction’, ‘open tasks’, ‘schedule pressure’, ‘design error’, and ‘change order’ items in the Rework, Design Error, and Change Order subsystems.

Rework also causes low productivity in construction, representing a negative link between the ‘rework during construction’ and ‘productivity in construction’ items. This might lead to conflicts between the stakeholders (a negative link), resulting in less supervision (a negative link), poor project management (a positive link), and more rework (a negative link). These close a reinforcing loop (R) among the ‘rework during construction’, ‘productivity in construction’, conflicts between personnel’, ‘supervision’, and ‘project management’ items in the Rework and Productivity subsystems (see Figure. 4.4 in Chapter 4).

Design error causes change orders and reduces the quality of design (a negative link). Poor design quality raises the quality pressure (a negative link), resulting in low productivity in design (a negative link). This forces more two-way communication (a negative link) to reduce open tasks (a negative link), schedule pressure (a positive link), and design errors (a positive link). These close a balancing loop (B) among the ‘design error’, ‘design quality’, ‘quality pressure’, ‘productivity in design’, ‘communication and coordination’, ‘open tasks’, and ‘schedule pressure’ items in the Design Error subsystem.

Change orders, due to rework and design errors, could be reduced through better planning and scheduling and a clear construction method. These represent negative links between the ‘change order’ and ‘planning and scheduling’ items, and the ‘change order’ and ‘construction method’ items in the Change Order subsystem. Less change orders result in less rework, which reduces open tasks, work pressure, and design errors (positive links). These, in turn, minimize change orders, and close a reinforcing loop (R) among the “change orders”, “rework during construction”, “open tasks”, “schedule pressure”, and “design error” items in the Change Order, Rework, and Design Error subsystems.

Rework, change orders, and design errors lower the productivity in the Productivity subsystem, and cause shortages of materials and design changes in the Design Change subsystem (see Figure 4.4 in Chapter 4). Low productivity in construction causes work conflicts between personnel (a negative link), high workers' absenteeism (a positive link), low skilled-worker availability on-site (a negative link), and low productivity (a positive link). These close a reinforcing loop (R) in the Productivity subsystem.

Interrelationships among five key construction delay factors and their associated items, as depicted in the causal loop diagram above, are used to develop the dynamic model to plan for reduction of construction delay in the long term.

5.3 DEMATEL-SD Model of Construction Delay

This study utilizes the five key construction delay factors and their associated variables to examine their comprehensive dynamics relationships, and how they affect project schedule using the so-called DEMATEL-SD modelling approach. DEMATEL analysis, on one hand, enhances a comprehensive understanding of construction delay factors, their influences on the others, and their impacts on construction delay. SD modelling, on the other hand, is an effective technique in construction project management with the potential to contribute to decision-making in a complex system. It considers the causal feedback relationships among construction delay factors, and how those factors affect the project schedule. Therefore, the DEMATEL-SD model approach is adopted in this study to effectively capture the dynamics behaviors of construction delay factors. It is expected that the study results provide a better understanding of key construction delay factors and their influences on project schedule, and also assist in developing effective policies to resolve the issues of project delay and complete the project within the schedule".

The DEMATEL-SD model of construction delay is as shown in Figure 5.2.

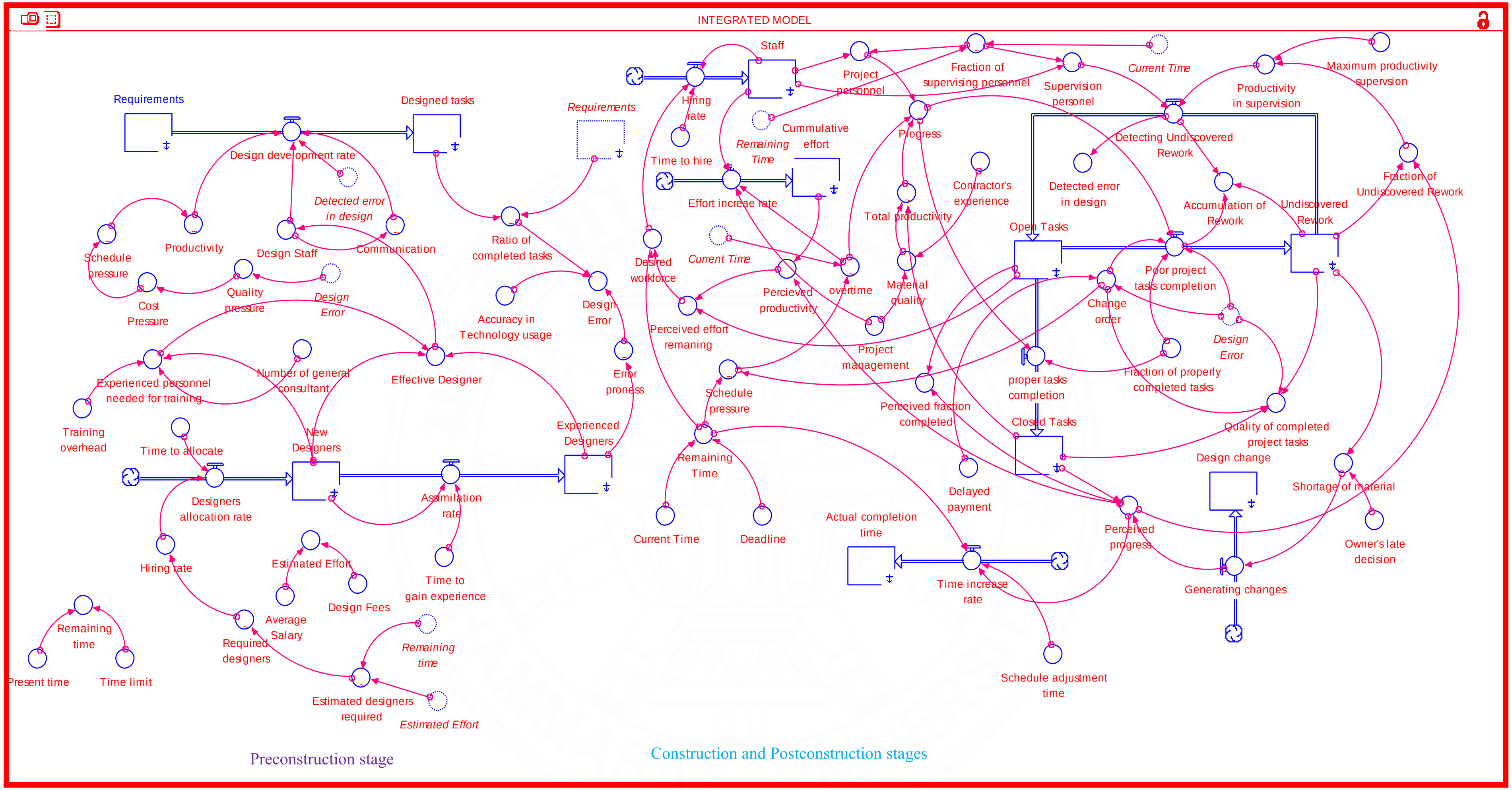

Figure 5.2 DEMATEL-SD model of construction delay

5.3.1 Data Used in the DEMATEL-SD Model Development

Data hybridization for investigations avert restrictions, thus making the studies embedding and encapsulating with diverse perspective to enhance robustness in results. Das and Emuse (2017) and Moselhi et al. (2005) integrated data set of economies with similar characteristics (secondary data system) with the collated information from their base of research (primary data). The obtained results can be adopted in other economies to address pertinent issues of project performance.

This study used both primary and secondary data in the DEMATEL-SD model development (see Table 5.1). Suslov and Katalevski (2019) and Love et al., (2008), for example, opined that an estimated of four designers are enough to contribute to progress and success of the design process in a typical work system. Suslov and Katalevski (2019) stated that design staff are being allocated to assigned to their tasks at a regular interval of four weeks. Wang and Yuan (2017) posited that in most cases, there is a need for adjustment in project scheme as a result of changes in requirements or tasks, and the earlier the adjustments are made, the better the results are. To that, there is an assurance of a better project performance, if project scheme could be adjusted early at the beginning of the construction process (i.e., within the 8th week).

Numerical values achieved from DEMATEL analysis results are also used in the dynamic model development. For example, the influence weight of design error (a key factor that depends on communication, experience, and technology accuracy) is 0.2. This results in the magnitudes of the technology accuracy of 0.03-0.07 based on the uniformity in influence of parameters (Chaker et al., 2015). This technique is applied to other variables in which values are established via the DEMATEL analysis results. Comprehensive details of pertinent variable values are given in Table 5.1 below. The model encapsulates several independent variables with constant values and independent variables connected to other variables with mathematical equations, which are all provided in the study.

Table 5.1 Data used in the development of the DEMATEL-SD model of construction delay.

Variable	Value	Unit	Explanation	Source
Change order	0.1-0.2	Unit	0.1 = the lowest change order value 0.2 = the highest change order value	DEMATEL analysis results
Contractor's experience	0.02-0.1	Unitless	0.02 = the lowest contractor's experience (maximum of 2 years of working experience) 0.1 = the highest contractor's experience (minimum of 10 years of working experience)	DEMATEL analysis results
Delayed payment	0.004-0.1	Unitless	0.004 = the best-case scenario depicting the situation where payment is being delayed by a maximum of 4% of the scheduled payment time 0.1 = the worst-case scenario where the payment is being delayed by 10% of the scheduled payment time	DEMATEL analysis results
Design change	0.194	Unit	Upper bound and default value of design change	DEMATEL analysis results
Design error	0.0047-0.2	Unit	0.0047 = the lowest value (the best-case scenario) deduced from a design process with adequate technology, experienced designers, effective communication 0.2 = the highest value (the worst-case scenario) depicting a significant level of error in the design process	DEMATEL analysis results

Fraction of properly completed tasks	0.6	unit	Upper bound and default value for fraction of properly completed task to monitor the pace of conformity of completed tasks with specifications (as established)	Ogano (2016)
New designers	4	persons	The system is put to work for a default value of 4 ascribed to the parameter (as opined)	Suslov and Katalevsky (2019)
Number of supervisors	2	persons	The work process is set to run by a default value of two supervisors (as established)	Ogano (2016)
Owner's late decision	0.02-0.1	Unitless	0.02 = the lowest value (the best-case scenario) depicting a maximum of 2% inconsistencies of total decisions 0.1 = the highest value (the worst-case scenario) representing the significant magnitude of lateness in decision, depicting a minimum of 10% inconsistencies in the total decision made by the owner	DEMATEL analysis results
Planned project schedule	232	weeks	Scheduled project completion time (as established)	Experts' opinion
Project management	0.1-0.53	Unit	0.1 = the lowest value of project management (the worst-case scenario) 0.53 = highest value of project management (the best-case scenario) depicting the effectiveness in provision of	DEMATEL analysis results, Ogano (2016)

			quality materials and tasks assignment to project staff	
Project tasks	10000	units	The work process is set to run with the default value (as established)	Wang and Yuan (2017)
Rework	0.2	Unit	Upper bound and default value for rework	DEMATEL analysis results
Schedule adjustment time	8	weeks	Changes could lead adjustment in project scheme. Therefore, the system is initialized with a default value of eight weeks for the parameter (as established)	Wang and Yuan (2017)
Technology accuracy	0.03-0.07	Unitless	0.03 = the lowest value representing the usage of standalone software 0.07 = the highest value depicting the integration of at least two design software	DEMATEL analysis results
Time to allocate staff to specific tasks	4	weeks	Default value to mortgage project participant (as established)	Suslov and Katalevsky (2019), Love et al. (2008)
Time to gain experience	4	weeks	Default value for the parameter (as opined)	Suslov and Katalevsky (2019)
Training overhead	0.25	Unitless	Default value depicting a scenario where one expert is assigned to train four new designers (as established)	Suslov and Katalevsky (2019)

The Design-Bid-Build (DBB) project delivery system, also known as the traditional method of project delivery, is the delivery system considered in this study. It is the oldest and most familiar project delivery method with the largest market share (Kubba, 2017). In this delivery system, the client enters a separate agreement with the consulting and contracting companies, commissioning to execute the design and construction tasks, respectively (Ghadamsi & Braimah, 2016). The DBB procurement system is a leading method and has unarguably been the most adopted method of delivering project owing to its long-time existence and cost advantage (Ali et al., 2014; Ghadamsi & Braimah, 2016; Okorie et al., 2017).

Project design is a core of construction projects. This study considers a typical large-scale construction project with an average project design fee of 16,861,960 Baht, and an average salary of 30,770 Baht per month per staff (Love et al., 2008). The project is scheduled to be completed within 232 weeks: 23 weeks (162 days) in the preconstruction stage, 200 weeks for construction stage, and 9 weeks in the postconstruction stage (i.e., 209 weeks altogether in the construction and postconstruction stages). The planned project tasks are 10,000 units (Wang & Yuan et al., 2017). The preconstruction stage consists of 996 tasks, while the construction and postconstruction (closure) stages consist of 9,004 tasks.

In a practical production system, new staff needs training to blend with the technicality of the set tasks and the task flow. Therefore, there is a need to establish a training mechanism to get new staff adapted to the work system. It is opined that an experienced designer is used to train new designers, hence, incurring the training overhead cost. For effectiveness, there is a need for one experienced personnel to train four new designers (Suslov & Katalevsky, 2019). With experienced designers, design adjustments during construction could be minimized to avoid calamitous project setback (Wang & Yuan, 2017).

For clarity, the integrated DEMATEL-SD model system is comprehensively explained in sub-models of key construction delay factors. Details are as follows.

5.3.2 Rework Sub-Model

Rework, being the most influencing factor and the core of project process, is “modeled to be associated with supervision and project management (see Figure 5.2). In addition, Rework factor is also affected by Design Error, Change Order, and Productivity factors (as a result of DEMATEL analysis). These are reflected in the “poor project tasks completion” in Equation 5.1 and “undiscovered rework” in Equation 5.2. With better supervision and project management, together with less design errors and change orders, the undiscovered rework could be reduced, resulting in high work progress and productivity (see Figure 5.2). This is consistent with Love et al. (2008) that design error contributes greatly to the total amount of rework experienced in construction projects, which later results in schedule delay. Rework detection rate (which is a function of supervision personnel and productivity in supervision) is crucial as it determines the quantity of open tasks at a particular instance of time. The rework detection rate (represented as ‘detecting undiscovered rework’ in the model) helps in determining the quantity of correctly completed tasks (i.e., closed tasks) at a particular point in time. The expression for ‘detecting undiscovered rework, is given as Equation 5.3. Fraction of undiscovered rework, which is used to modulate the ‘productivity in supervision’ variable, is a function of perceived progress and undiscovered rework. The project completion time is, therefore, a function of the project progress and the scheme adjustment time. Timely detection of rework by project supervisors is an enhancement to better project performance in terms of time. These details prove the importance of the rework cycle to project process.

$$Poor\ project\ tasks\ completion$$
$$= Progress * (1 - Fraction\ of\ properly\ completed\ tasks) * (Design\ error + Change\ order) \quad (5.1)$$

$$Undiscovered\ rework$$
$$= Poor\ project\ tasks\ completion - Detecting\ undiscovered\ rework \quad (5.2)$$

$$Detecting\ undiscovered\ rework$$
$$= Productivity\ in\ supervision * Supervision\ personel \quad (5.3)$$

As the simulation run is initiated, series of open tasks are being processed to be executed. Tasks that are properly executed flow into the “closed tasks” stock, while the poorly completed tasks move to the stock for “undiscovered rework”. The rate at which the poor completed tasks move to the stock for undiscovered rework is measured by the “poor project tasks completion”, which depends on errors in the project design, thus facilitating changes, and rework. The “closed tasks” stock influences the magnitude of productivity as tasks are being reworked according to specification. Also, according to DEMATEL results, rework impacts design change. Therefore, the simulation runs initiate the system to collate the magnitude of changes that occur during the project as a result of rework.

5.3.3 Design Error Sub-Model

According to Ham et al. (2018), design error is a key delay factor that emanates at the preconstruction stage. This factor contributes significantly to project delay and should be comprehensively considered to minimize delay. In a typical DBB system, key stakeholders involved in the preconstruction stage include owners, consultants, and designers. The Design Error sub-model focuses on the preconstruction stage's design workflow, by encouraging communication among key stakeholders, and utilizing advance technology and experienced designers to minimize design errors before the commencement of the construction processes to save the project from colossal delay. In the Design Error sub-model, design development rate depends mainly on number of staff in the design team, productivity in design, and levels of communication between the design team and other stakeholders (see Figure 5.2 and Equations 5.4-5.8).

$$Design\ development\ rate = Productivity * \left(1 - \frac{Communication}{100}\right) * Staff \tag{5.4}$$

$$Productivity = f(Schedule\ pressure) \tag{5.5}$$

$$Communication = f(Staff) \tag{5.6}$$

$$Design\ staff = f(Effective\ designer) \tag{5.7}$$

$$Designed\ tasks = 0(Initial\ value) \tag{5.8}$$

The effectiveness of the designers also depends on their experiences. In this study, four new designers are considered at the beginning of the project in expectation to complete the design work on time. It is also hypothesized that there is a need for one experienced designer to train four new designers (Suslov & Katalevsky, 2019). The variable "effective designers", as shown in Equation (5.9), is a value depicting the collation of full-time experienced designer that can work on the design. According to Suslov and Katalevsky (2019) and DEMATEL analysis results, new designers have 80% productivity subjected to improvement by experienced designers.

$$Effective\ designers = 0.8 * New\ designers + (Experienced\ designers - Experienced\ personnel\ needed\ for\ training) \quad (5.9)$$

The stock of the "new designers" is a direct recipient of the "designers allocation rate" (see Equations 5.10 and 5.11), while the "required designers" is a function of the estimated number of designers, see Equation 5.12.

$$Designers\ allocation\ rate = Hiring\ rate /\ time\ to\ alocate \quad (5.10)$$

$$Hiring\ rate = f(Required\ designers) \quad (5.11)$$

$$Required\ designers = f(Estimated\ designers\ required) \quad (5.12)$$

The estimated required designers depend on two variables: the estimated effort and remaining time to complete the design tasks. If the time remaining to complete the design process is short, then the estimated number of designers needed to complete the firm's requirement would increase proportionally (see Equations 5.13 and 5.14).

$$Estimated\ designers\ required = \frac{Estimated\ effort}{Remaining\ time} \quad (5.13)$$

$$Estimated\ effort = \frac{Design\ fees}{Average\ salary} \quad (5.14)$$

The number of completed design tasks depend on the error proneness of the designers (i.e., mistakes from designers). According to Love et al. (2008), the design error proneness by expert designers, designers transferred from other projects, and new recruited designers are 10%, 20%, and 25%, respectively. In the DEMATEL-SD model, however, the design errors at the beginning are set at 20%, and it is assumed that new designers become experienced within 30 days of work.

Butlewski et al. (2014) mentioned that the use of high design technology helps reduce design errors. Reasonable level of accuracy in handling and applying advanced engineering design software debases design errors. Nevertheless, design error always exists. Even if design system can be operated without human intervention, the chance of design errors is still possible (Foord & Gulland, 2006; Busby, 2001). Since the owners define and control the project through the consultants, the consultants' roles are very sensitive in ensuring proper supervision of the design processes to avoid design errors (Kubba, 2012). In a typical DBB system, the design processes are concluded before the commencement of the construction process. Therefore, the consultants must facilitate effective communication, and provide advance engineering software to ensure reasonable level of design accuracy.

The design error (in % of error) is calculated based on Equation 5.15. With higher designers' experience, better communication, and better technology usage, design errors can be reduced, resulting in lower rework and change orders, and higher productivity (see Figure 5.2)".

$$Design\ error = Ratio\ of\ completed\ tasks * Error\ proneness * (1 - Accuracy\ in\ technology\ usage) \tag{5.15}$$

5.3.4 Design Change Sub-model

Based on the DEMATEL analysis results, design change is influenced by rework, which is particularly caused by shortage of materials during construction. It can be seen in the DEMATEL-SD model that rework influences design changes and may affect the whole project design and construction. The magnitude of changes is determined in the DEMATEL-SD model, so that owners and stakeholders can deal decisively with the problems, especially materials shortage from the preconstruction stage to minimize the problem of design changes during the construction. Magnitude of design changes is given as Equations 5.16 and 5.17. It depicts the fact that design change is a function of shortage of materials through rework.

$$Generating\ changes = f(Shortage\ of\ materials) \tag{5.16}$$

$$Shortage\ of\ materials = Undiscovered\ rework * Owner's\ late\ decision \tag{5.17}$$

In Equation 5.17, shortage of material is a function of undiscovered rework and owner's late decision. Therefore, the timeliness and accuracy in the decision system of project owner is important in minimizing the problem of material shortages on site.

5.3.5 Change Order Sub-Model

Amendment to construction may change the scope of work during construction. Changes may be induced by design errors, payment structure problems, cost reduction, or other pertinent reasons. In this study, Change Order factor relates with Design Error factor, as a result of DEMATEL analysis. Less design errors, therefore, lead to less change orders (see Equation 5.18). Delayed payment in Equation 5.18 determines the magnitude of change orders, as it affects stakeholders' decision to proceed with work due to financial difficulties (Alaryan, 2014).

$$Change\ order = (Design\ error * Delayed\ payment) \tag{5.18}$$

5.3.6 Productivity Sub-Model

Productivity is the key factor in the postconstruction phase. "Based on the DEMATEL analysis results, this factor is influenced by Design Error, Rework, and Change Order factors. Once design errors are detected, some completed tasks are to be redone; this reduces the productivity. Increase in productivity is achieved once repeated projects are performed and that design errors, change orders, and rework are reduced through experiences, better technology, good project management, high quality equipment, motivation, and staff encouragement, thus reducing delay of the whole project (see Figure 5.2, and Equation 5.19). Debasing the threat of design errors, change orders, and rework increases the quantity of the closed tasks (i.e., correctly completed tasks), which in turn improves total productivity.

Total productivity is modelled to be a function of closed tasks and material quality being induced by project management system and contractor's experiences. Effective project management does not only reduce rework, but also improve productivity and minimize schedule delay of the projects.

$$Total\ productivity = Closed\ tasks * Material\ quality * Contractor's\ experience \tag{5.19}$$

In summary, the early stage of construction (preconstruction phase) is being faced with various problems, ranging from design errors, frequent changes, low supervision, inability of staff to adapt to construction processes, and high rework, resulting in poor completed tasks and delay of the project. Once the project continues, workers get adapted to the processes, project supervision becomes more effective, and tasks are completed according to owner's specification. These results in the increase of properly completed tasks and total productivity, thus reducing rework and delay in the construction and post-construction phases".

5.4 Simulation Results

The developed DEMATEL-SD model of construction delay is simulated to examine the construction delay in the long term. Variables in the model are set up for several simulation runs with default values (as shown in Table 5.1) and corresponding equations. The connection between the preconstruction and construction phases are found in the Design Error and Rework sub-models where some units of incorrectly completed tasks, as a result of design errors in the preconstruction phase, are detected as rework during construction, and must be corrected before those tasks are closed. Design errors also generates changes during construction, which in turn causes rework and results in poor productivity in the postconstruction phase.

The default value of design error, combined with other delay variables at their default states, are used in the first simulation run, and the simulation results reveal the worst-case scenario with the delay of project completion of 16 weeks (i.e., project completion of 248 weeks). In the subsequent simulation runs with similar projects performed, the minimized values of the delay factors within the intervals described in Table 5.1 induce changes in the values of other dependent variables in the system, which in turn determine the project progress. For example, the magnitude of design error being minimized reduces change orders and rework cycle. With less undiscovered rework, closed tasks (i.e., tasks correctly completed) increase, thus enhancing the productivity of work. The quantity of the closed task is used to measure the total productivity and the project progress.

The exogenous variables in the model, which are the key delay factors in the study, are initiators of the several endogenous variables that are changed with improvement of the delay factors. For instance, the Design Change factor (an exogenous variable), which is influenced by rework, determines the "perceived progress" variable (an endogenous variable), which in turn affects the "perceived productivity" and "cumulative effort" variables (endogenous variables) in performing the project tasks. The dynamic changes of these factors result in different project completion time. It is, therefore, important to mention in a more concise term that minimizing the values of the delay factors impact the pertinent endogenous variables (e.g., productivity, progress, and cumulative efforts) to determine the actual project completion time. Consistent minimization of design errors, changes during construction, and rework improves productivity, and in turn, reduces the project delivery time.

The simulation results, as shown in Figures 5.3-5.5, show that latter similar projects perform better than former ones in terms of time. This is attributed to the minimization of the responsible delay factors depicting the fact that better project performance in terms of time is an attainment that can be achieved over time when the threat of the prominent delay factors is significantly subjugated.

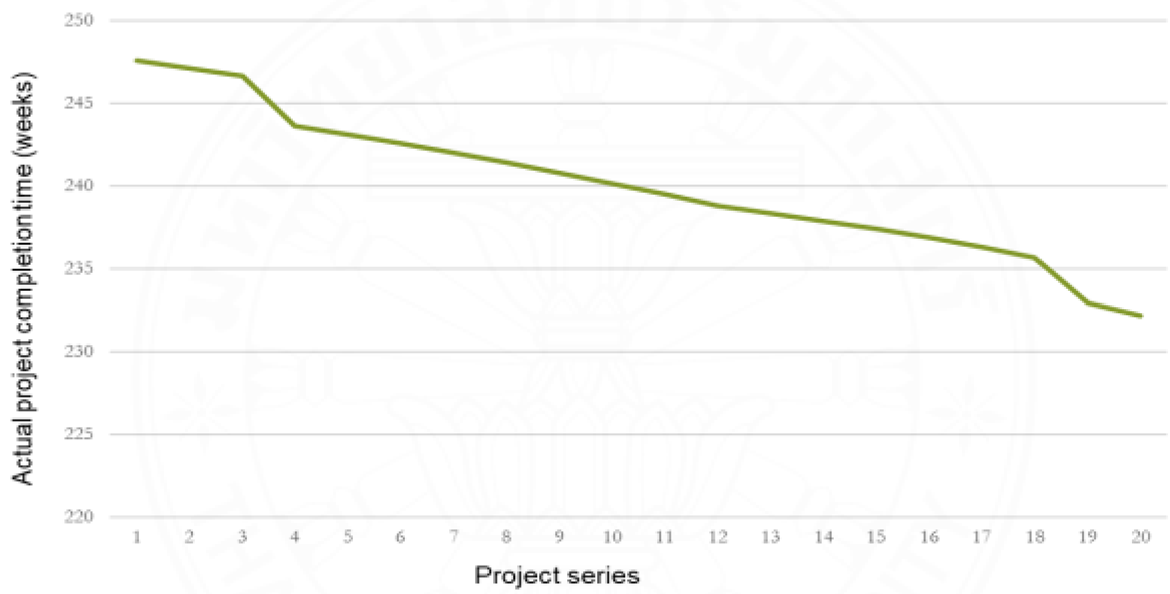

Figure 5.3 Actual completion time of construction projects

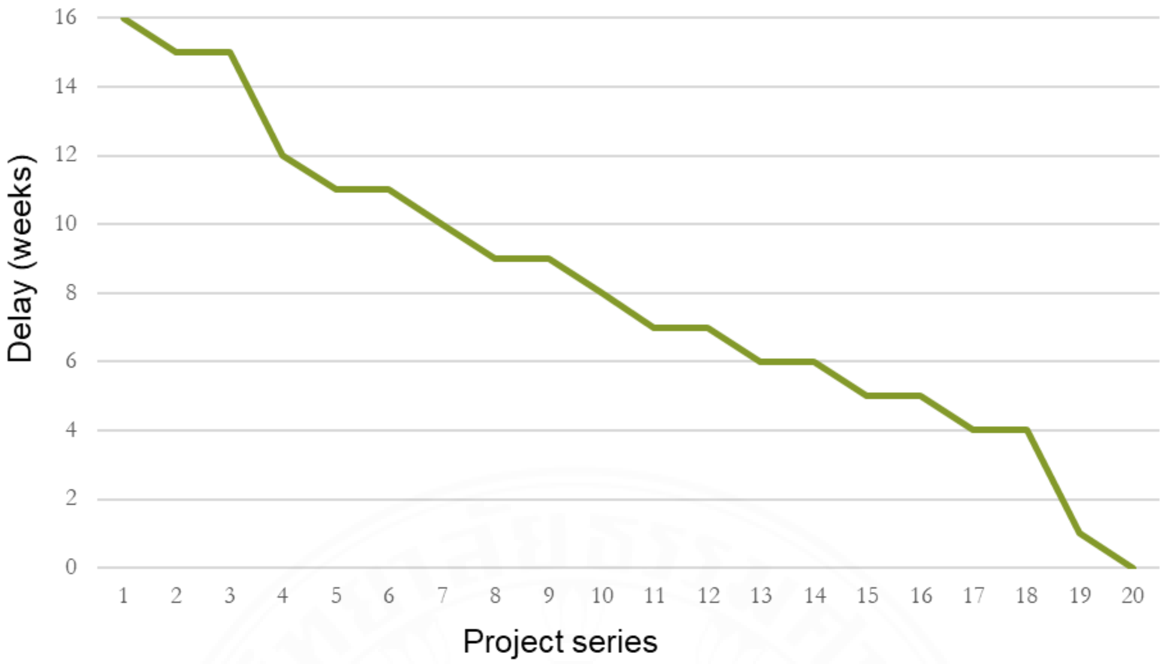

Figure 5.4 Delay magnitude of construction projects for different project series

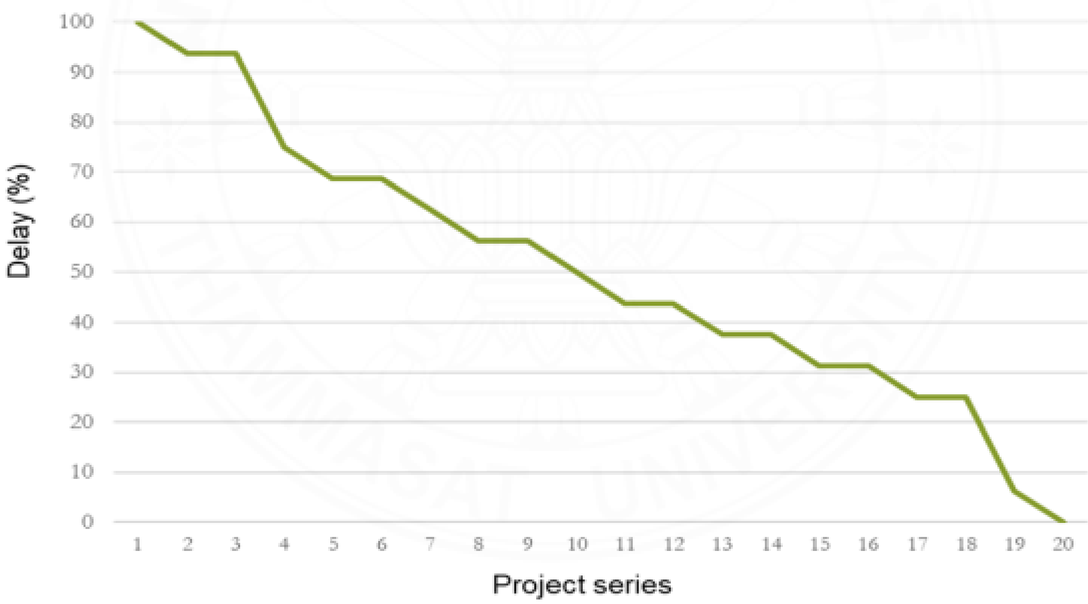

Figure 5.5 Delay percentage of construction projects for different project series

The simulation results, see Figures 5.3 - 5.5, show that “with no consideration of five key construction delay factors, the construction companies face the delay of a maximum of 16 weeks i.e., 248 weeks of completion time. This could be seen in the early projects. Once similar projects are performed and improvement of the five key delay factors are implemented, the construction companies can reduce the construction delay to meet the deadline of 232 weeks as planned. It is important to mention that the horizontal axis labelled “Project series” denote similar projects performed sequentially in succession of time.

Closer examination of the project at the beginning (the 1st project) reveals that at the end of the 232nd week, the closed tasks are 8,899 out of 10,000 tasks. It is found that the delay in the preconstruction stage results in unfinished closed tasks in the construction and postconstruction stages. This early-stage delay comes from inexperience of designers. Once the projects are repeated, with better technology usage and experienced designers, the design error reduces from 20% to a minimum of 0.47% (as absolute design 0% error is impossible). Less design errors in the preconstruction phase reduce rework, change orders, and design changes in the construction phase, thus increase the productivity in the postconstruction phase. It can be seen in Figures 5.4 and 5.5 that the delay is reduced once the five key construction delay factors are considered and improved”.

5.5 Model Validation

“Model validation is the process of determining whether the model accurately represents the behavior of the system. This process enhances the confidence of the model to represent the real-life situation it seeks to emulate (Gilkinson & Drangerfield, 2013). Two major validation processes are adopted in this study to build confidence in the established integrated hybrid model. They are 1) the experts’ ratification and validation process and 2) the sensitivity analysis (also known as the policy testing) (Saltelli et al., 2004; Yusoff, 2019). They are used in several real-life problems to increase confidence in the developed dynamic model.

5.5.1 Experts’ Ratification and Validation

Experts’ ratification and validation process is established to analyze key problems in an organization through eligible personnel and affirm that the base case behavior is in accordance with known reports or past data. The developed DEMATEL-SD model, which is formulated from the DEMATEL analysis results, is subjected to a validation process featuring league of industrial experts, inviting their opinions and contributions to the model, thus proving its use to plan for project performance. Six experts working in leading building construction companies in Bangkok and vicinity provinces in Thailand participated in the validation process. They are top executives, owners, and engineers with more than 20-year working experiences in large-size building constructions, with an average of 100 million Baht in capital investment and over 100 operators. These number of experts with their characteristics are adequate for the validation process (Yusoff, 2019). A preliminary information was shared explaining how the

DEMATEL-SD model is developed. This helped the experts understand how the model worked. Experts were asked to review the model and gave comments which made it important to include some endogenous parameters like “schedule pressure”, and “overtime” to induce “productivity” and “work progress” respectively, which in turn improve the model. The model is subsequently adjusted based on their recommendations and comments to reflect real practices.

5.5.2 Policy Testing Analysis

In this study, the behavior-sensitivity test is referred to as the policy testing analysis. It focuses on the sensitivity of the model’s behavior to changes in parameter values. It is conducted by experimenting with different parameter values and analyzing their impacts on the system (Forrester & Senge, 1980). It is one of the most effective methods used to build confidence in SD models. In this study, the policy testing analyses are performed by changing values of variables in each key factor to examine the sensitiveness of the developed DEMATEL-SD model and investigate the delay in the long term.

5.5.2.1 Policy Testing of the Design Error Factor

Policy testing is performed in this study to achieve the strategies the construction companies can perform to complete the project on time. As Design Error is a crucial factor in the preconstruction stage, and that this factor depends on the designing team and technology used in the design (see Figure 5.2), the policy testing is then performed by changing the technology accuracy (TA) values, from 0.03 to 0.07. The results, as depicted in Figure 5.6, show that the developed DEMATEL-SD model is not sensitive, as model behavior is not changed. The results also reveal that the use of low design technology results in more delay of the whole project, as design changes, rework, and change orders occurred in the construction stage”.

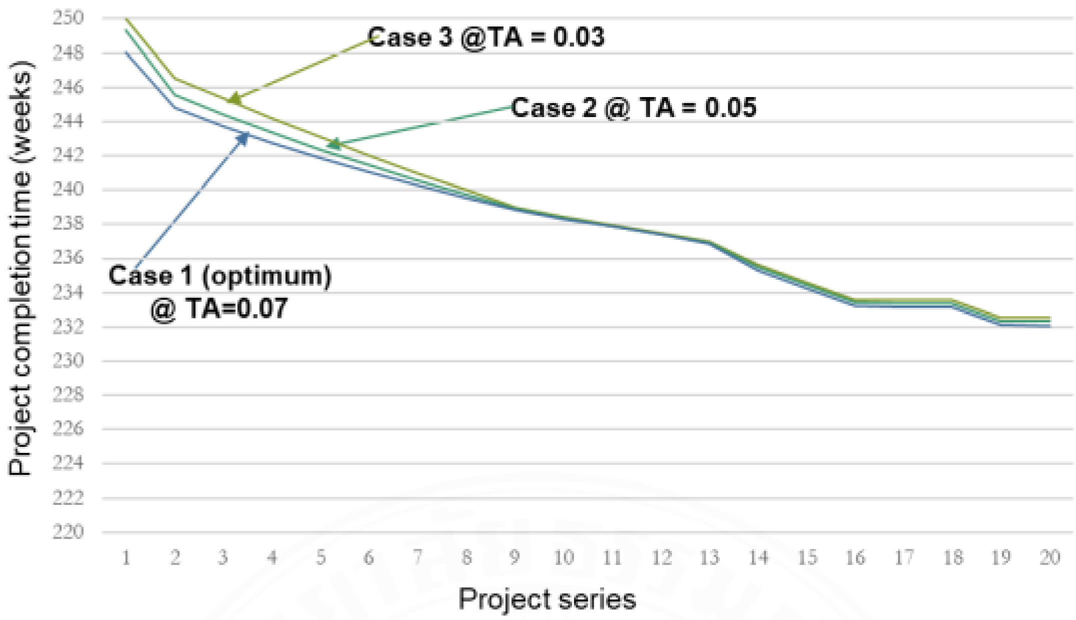

Figure 5.6 Sensitivity analysis of project completion time when various degrees of technology advancement are changed

The “impact of technology on the design process and the entire project is immense, as low technology input impacts the project schedule negatively. With the optimum value of technology accuracy (i.e., TA @ 0.07), the time lag in delivering the project is reduced compared with other values of technology accuracy (see Figure 5.6). The impact of reasonable accuracy in technology thus makes the design processes to be completed with minimal error and contributes significantly to the timely project completion.

A number of existing advanced design software are functions of advancement in technology, which also demand high level of expertise and experiences in applying them in project designs. Effective engineering design software is crucial in modern construction work. Rhino 3D, Revit Architecture, Sketchup, V-Ray, Maya, ArchiCAD, Grasshopper, Dynamo, and Fusion 360 are examples of effective design software used in the construction industry (Archistar, 2020). The performance and accuracy of the design process depend on the effectiveness in handling these technology-birthed software. Some of this software are standalone software (i.e., they can be used independently), while some must be integrated with other software for better performance. For example, V-Ray can be integrated with ArchiCAD and Sketchup to enhance design processes (Archistar, 2020). In this study, the use of standalone software corresponds with technology accuracy of 0.03, combination of two software corresponds to technology accuracy of 0.05, and the integration of three software corresponds to technology accuracy of 0.07, representing the best-case scenario.

Figure 5.6 shows that once similar projects are performed, project design gets better as a result of the experiences gained by the designers. This explains the convergence of the three lines at the later projects no matter the degrees of technology advancement considered. Therefore, it is important that designers undergo training of design technology, so that it can be effectively applied to enhance the design accuracy. Technical know-how (i.e., technology usage) and experience are not independent on each other, and that they must be enhanced to mitigate errors. It is, therefore, noteworthy that as companies invest in project design technologies, it is also important to invest in designers' capabilities to achieve the better project performances and minimize delay at the beginning of the projects.

5.5.2.2 Policy Testing of the Rework Factor

Rework is a critical factor in the construction phase, and effective supervision is needed to detect rework at the beginning of the construction. For a typical large-size project with a minimum of 100 staff, myriads of activities are embedded, which may require decent number of experienced supervisors. In a typical work process, number of supervisors involved in work processes relate with number of staff and project sizes. Project staff need adequate supervision to ensure productivity and timely rework detection. In this study, two project supervisors are assigned to supervise the project staff, meaning that each supervisor is responsible to monitor the work progresses of at least 50 staff. More supervisors, if have, could help to ensure proper tasks completion and conformity of completed tasks to specifications.

The policy testing is then performed by changing supervision personnel (PS) from 2-4 persons (see Figure 5.7). The results show that with better supervision, the projects can be completed on time. Increasing value of supervision personnel ($2 \leq PS \leq 4$) reduces the magnitude of delay by enhancing productivity in supervision, thus facilitating early detection of rework. Faster convergence of the project is guaranteed with higher number of project supervisors".

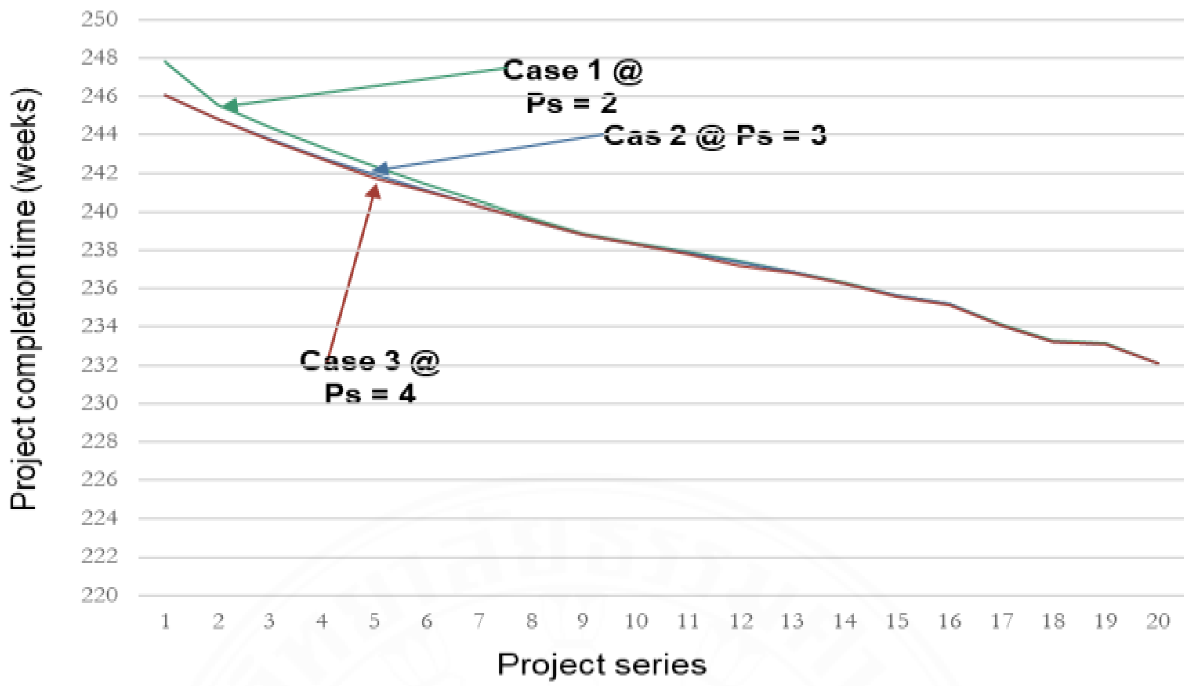

Figure 5.7 Sensitivity analysis of project completion time when number of supervisors are changed

Based on Figure 5.7, it is found that having more than three supervisors, does not further reduce the delay of the whole project. This explains the fact that involving more supervisors than needed might not make significant impact to the project, especially in a situation where the construction space is limited. This is consistent with Wang and Yuan (2016) that size of the construction site determines the number of projects participating staff, as too many project participants could lead to overcrowding and low work rate, which in turn, hamper project performance. Moreover, recruiting more supervisors than required could lead to ineffective supervision, causing late rework detection, low productivity, and absenteeism. Figure 5.7 also shows that the graphs merge after similar projects are repeated. This could be explained that once supervisors gain experiences through similar projects, work performance increases and delay is minimized.

Apart from number of supervisors, project management is crucial in determining the progress of the project during the construction (Ogano, 2016). Procurement and construction are considered as one of the major stages of project management. The procurement system determines the availability of quality materials, effective usage, and facilitation of reliable and robust construction processes (Matheu, 2005). An effective project management ensures that project members are assigned to specific tasks, and effective monitoring of project progress is performed (Purdue University, 2021). Therefore, in this study, the policy testing is performed by changing the project management (PM) values from 0.1 (default value) to 0.53 (effective project management based on the DEMATEL analysis results). The default value corresponds to a project management system void of consistent and effective provision of quality material and tasks assignment to staff. Project management of 0.3 represents an improved system of designation of staff to specific tasks, while 0.53 represent an effective project management system with effective and consistency in the supply of quality material, and a reasonable level of accuracy in assigning and mapping staff to specific assignments or tasks. An effective project management system is void of acute corruption system and provision of weak construction materials. The results, as shown in Figure 5.8, prove that increasing value of project management reduces the project time lag. With better project management, tasks are assigned to project parties accordingly without bias and prejudice, thus allowing effective monitoring of the work progress, and finally reducing the construction delay.

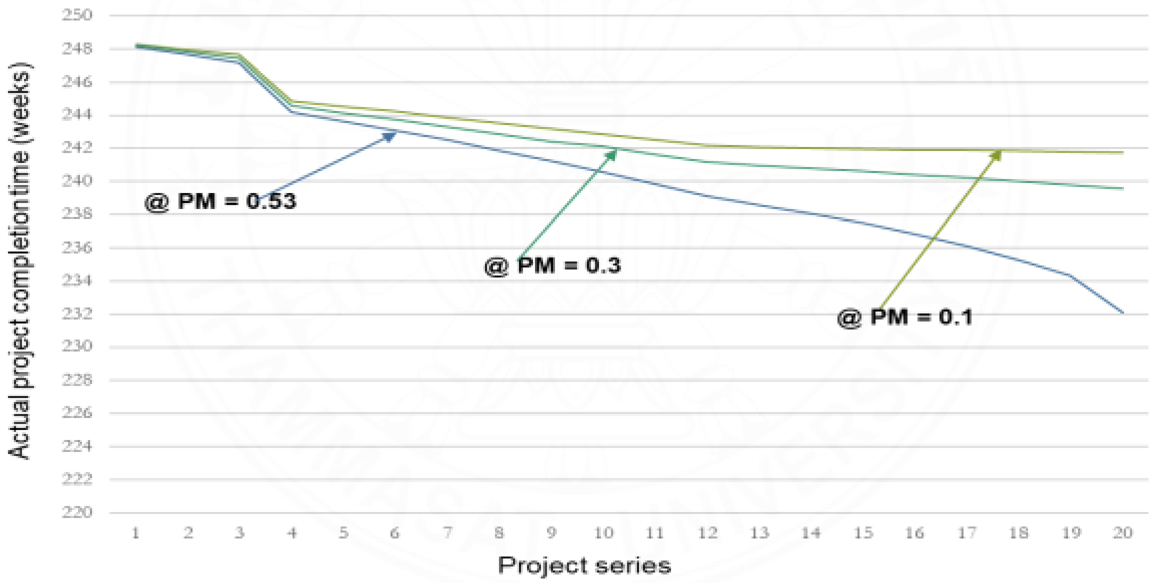

Figure 5.8 Sensitivity analysis of project completion when project management values are changed

5.5.2.3 Policy Testing of the Change Order Factor

Delayed payment is an associated sub-criterion of the Change Order factor that affects the entire project schedule. Clear owner's financial and payment plan could reduce problems of change orders (Khoso et al., 2019). Involving the owner in the design process could enhance the owner's understanding of project plan and reduce changes in the owner's requirement, as these changes could affect the procurement system, and lead to contractor's improper construction method and changes in materials during construction. Shortage of fund, as a result of frequent material changes, could cause difficulties in financing project, leading to delayed payment and finally postponing the project completion time.

The policy testing is performed by changing the values of delayed payment (DP) from 0.004 (best case scenario with prompt payment) to 0.1 (worst case scenario with payment being delayed by 10% of the scheduled time). The results show that by increasing the value of delayed payment, the project completion time increases (see Figure 5.9). This is consistent with Akinsiku and Ajayi (2016) that delayed payment negatively impacts project schedule. Project stakeholders should, therefore, ensure timely payment to boost staff morale and enhance better project performance in terms of time. When project owner makes adequate financial preparation before the commencement of the project, the problem of delayed payment is significantly reduced.

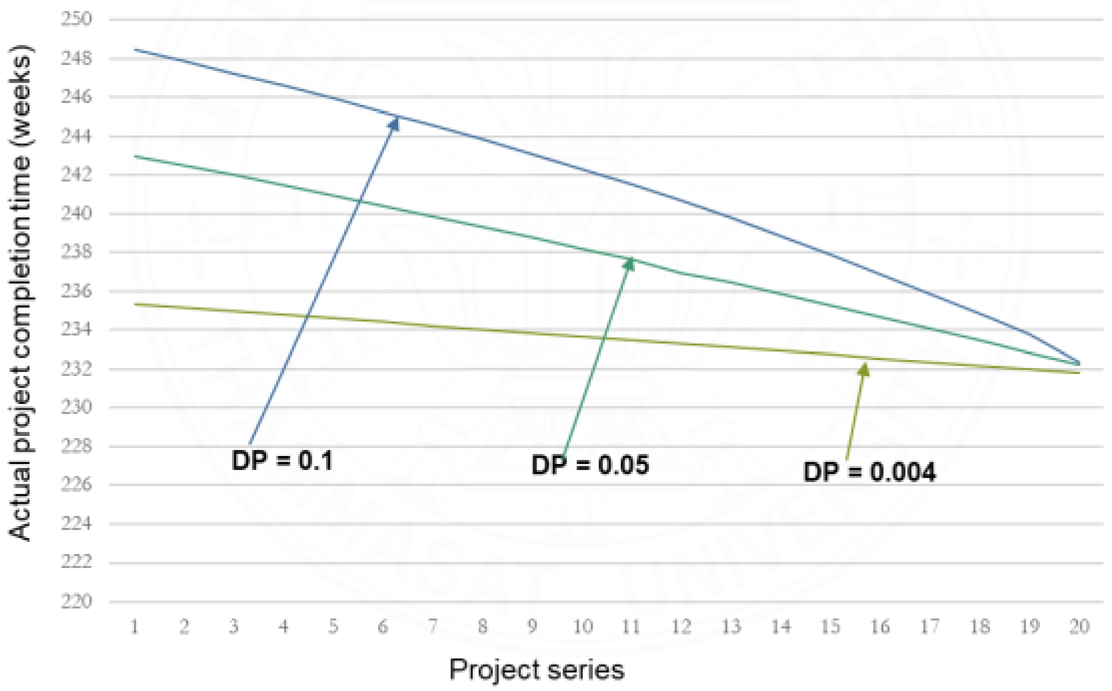

Figure 5.9 Sensitivity analysis of project completion time when values of delayed payment are changed

5.5.2.4 Policy Testing of the Design Change Factor

Owner's late decision is an associated sub-criterion of the Design Change factor that affects the materials availability, which in turn, affects the project schedule. Koo et al. (2009) stressed that decision makings on construction project impact the project significantly. It is important that project owners ensure timely decision by facilitating adequate and regular funding, cooperating and collaborating with stakeholders, and effectively planning to ensure materials availability on site to avoid the delay. In this study, therefore, the policy testing is performed by varying owner's late decision (Old) values from 0.02 to 0.1, where the value of 0.02 represents the best-case scenario, depicting low magnitude of poor decision system by the owner in providing necessary support for the project participants, and the value of 0.1 represents the worst-case scenario, depicting a significantly poor and late decision system by the owner. The simulation results, as shown in Figure 5.10, show that the decision process of the project owner regarding material availability has a slight effect on project completion time, especially in the preconstruction stage or at the beginning of the project, as changes may still occur during the construction.

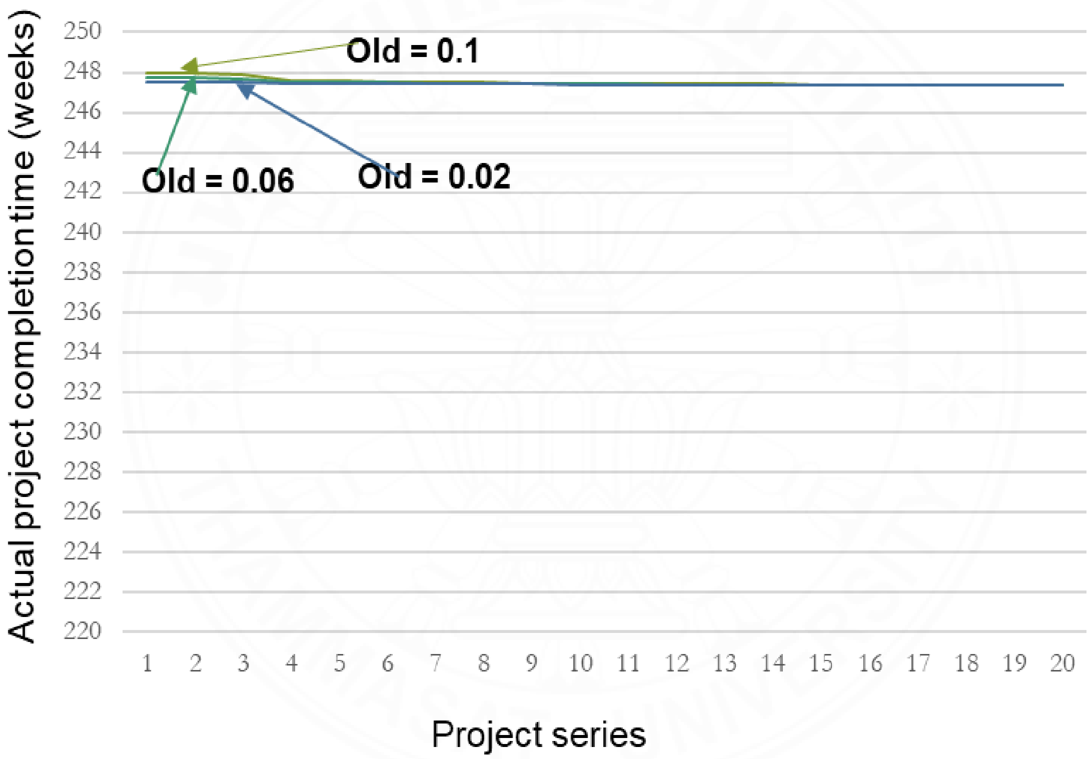

Figure 5.10 Sensitivity analysis of project completion when the values of owner's late decision are changed

5.5.2.5 Policy Testing of the Productivity Factor

Construction contractors have colossal influences on project success and performance (Huang, 2011). The competence of contractors, which is a function of experiences, is a key in timely project completion. Therefore, owners and consultants should select experienced contractors to oversee the construction processes, and provide high quality work through quality workers, equipment, and materials. The contractor, who is a key stakeholder at the construction stage, must display reasonable level of experiences to minimize project time lag.

The policy testing is then performed by changing the values of contractor's experience (CE) from 0.02 (worst case scenario with 2 years of working experience in the construction sector) to 0.1 (best case scenario with at least 10 years of working experience in the construction industry). The results, as shown in Figure 5.11, confirm that the contractors with higher experiences contribute better time performance.

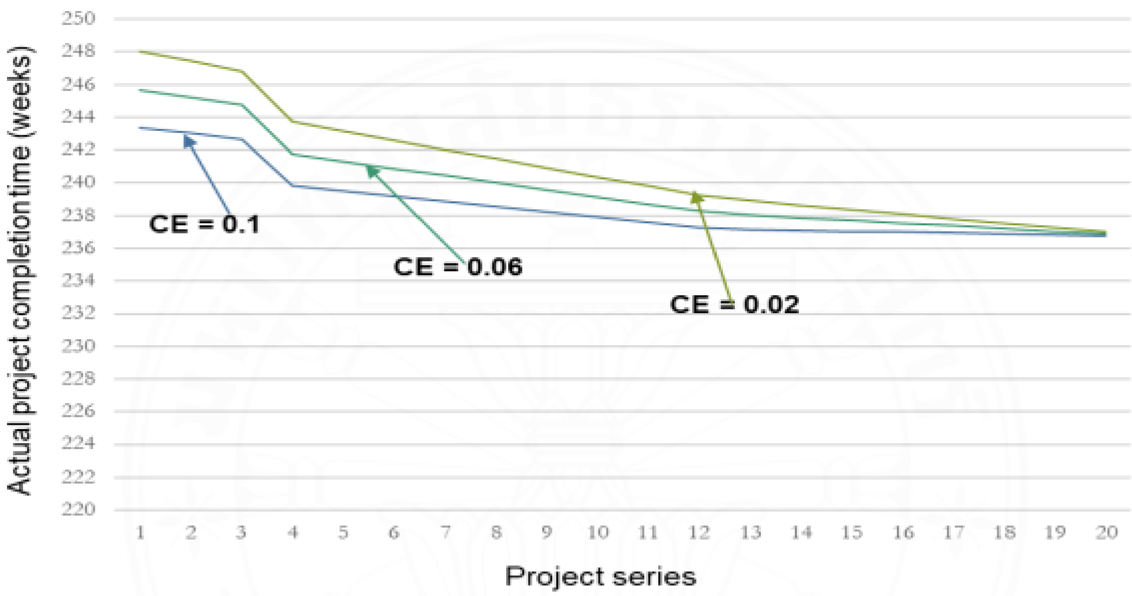

Figure 5.11 Sensitivity analysis of project completion time when the values of contractor's experience are changed

5.5.2.6 Comparison of the Policy Testing Results

The best-case scenarios of the policy testing of the five key delay factors are plotted against each other, as shown in Figure 5.12. It could be seen that on-time payment is crucial in getting the project completed on-schedule, as materials could be ordered and delivered as planned, and workers are motivated through on-time payment. Workers usually rely on regular payment to pay for their livings. On-time payment, therefore, raises their motivation and spirit.

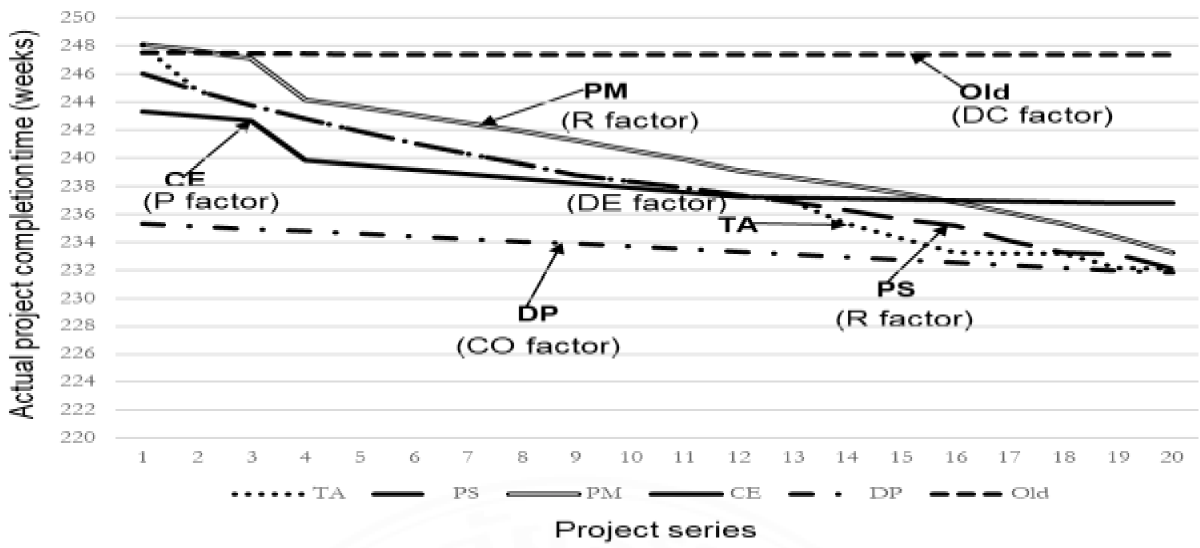

Figure 5.12 Summary of best-case scenarios of the policy testing

5.6 Discussion of the Results

Design Error is a key factor at preconstruction stage that affects the entire project schedule. Necessary criteria are used to subjugate threats of design errors to minimize the magnitude of other delay criteria at the later stages of the project. The simulation process with the default parameter values represents the first project with a colossal delay of 16 weeks. The consistent minimization of the five key delay factors reveals steady work improvement through similar projects with regular succession of time, thus reducing project delay in the long term. This underscores the importance of project stakeholders working assiduously in subjugating the prominence of the delay variables to enhance better project performance in terms of time. Also, other pertinent embedded criteria play important role in minimizing delay. For example, the use of advanced technology or an integrated system of design software reduces the magnitude of delay at the beginning of the project. Effective supervision, through a decent number of experienced supervisors, also enhances better project performance through timely rework detection by ensuring tasks are completed to specification. With steady and consistent improvement of the project management system, delay magnitude can also be reduced.

Delayed payment is found crucial in minimizing the construction delay. A timely payment system facilitates better project performance, as it helps raise workers' morale and productivity. The contractor's performance and experience are also vital to project performance, as it helps make timely and quality decisions at every stage of the construction processes.

The dynamics of the delay factors in the developed DEMATEL-SD model is an effective panacea to the monumental problem of project delay. It initiates significant improvement, especially when proper decisions are made following the policies highlighted in this study, as the construction industry needs a change and turn around in system in terms of project performance to avert the negative consequences of project delay and make the construction sector a better place.

CHAPTER 6
CONCLUSION

6.1 Overview

This chapter concludes the study, from DEMATEL analysis to the DEMATEL-SD model development and simulations. The contribution to the body of knowledge is pinpointed. Limitations and recommendations for future studies are included in the last part of this chapter.

6.2 Conclusion

Scheme performance is critical to construction project success. However, many construction projects experience significant time delay and fail to meet their schedule targets. The delay of these projects has colossal economic consequences. “This study adopts a novel approach to proffer solution to the menace of construction delay that emanates from the preconstruction stage and metamorphosizes into a thriving problem throughout the project. The consistent judgmental opinion of experienced experts is applied with the DEMATEL analysis method to examine the influence levels of key delay factors, namely Design Error, Rework, Change Order, Design Change, and Productivity, which serve as the basis for the DEMATEL-SD model development. The DEMATEL analysis results confirm that all key delay factors are prominent and influencing each other and construction delay with different degrees of influences. Rework, Design Error, Change Order, Productivity, and Design Change are have the influence weights of 20.4690%, 20.1198%, 19.9990%, 19.9467%, and 19.4655%, respectively. Results show that the Design Error factor is the influencing factor in the pre-construction phase, while the Rework factor is the most influencing parameter in the construction phase.

Based on the DEMATEL analysis results, the DEMATEL-SD model is developed not only to solve the menace of project delay, but also to show the importance of the mathematical system and solutions to key engineering and industrial problems. The developed DEMATEL-SD model is used to examine the relationships among the controlling factors of delay and their impacts on project schedule over time. It is embedded with several contributing parameters to depict the overall workflow processes and represent real-life work practices on the construction sites. The model consists of five sub-models, representing five construction delay factors and their associated variables. The Design Error factor is considered as a key delay factor at the preconstruction stage, influencing changes during construction, and altering the initial scope of work, resulting in high amount of rework that, which in turn, affects project quality and completion time. Therefore, it is important that design error be minimized at the beginning of the project to reduce change orders, design changes, and rework during the construction. Minimal design errors, achieved by reasonable level of technology accuracy, effective communication, and experienced designers, significantly reduce the magnitude of delay not only in the preconstruction stage, but also construction and postconstruction stages. Integrating effective digital design software with decent number of experienced designers enhances accuracy in the project design, thus reducing the magnitude of errors. Training new designers is also necessary, so that they become experts through steady improvement. The companies with low budget on technology improvement may consider keeping workers' loyalty in the companies as more experiences they gain in the work, less errors occur, leading to high productivity and minimum work delay.

Rework is found crucial in the construction phase. Effective supervision, birthed by experiences and active supervisors, can promptly detect rework during the construction, thus reducing the errors that may continue to the postconstruction stage. Improvement of Change Orders, Design Change, and Productivity factors through, for example, on-time payment, highly experienced contractor, and timely decisions of the owner enhances on-time construction project performance and minimizes delay in the long term. Contractors with high work experiences, for example, could address pertinent issues relating to productivity, construction methods, financing problems, and dispute amongst workers, thus helping the work problems to the minimal. Ability of the owners to make timely decisions on work specifications is also important to achieve the on-time project delivery. On-time payment system also contributes significantly to the timely project convergence, as project staff are encouraged to achieve significant level of productivity at every instance of time.

Extensive examination and effective management of construction delay controlling factors are vital to achieve a better project performance in terms of time. This study further examines influences of five key delay factors on project schedule through the policy analyses. The comprehensive dynamics of the project design cycle, changes during construction, rework, and productivity encapsulated in the integrated work process, are critically examined to debase the threat and magnitude of project delay from the beginning to the end of the project. Therefore, it is imperative for project stakeholders to make sure project scope and requirements are clearly spelt out at the early stage of the project to mitigate the threat of design errors that may lead to design changes, change orders, and rework during the construction, and low productivity and delay at the end of the project. Closing tasks demands high level of efforts and cooperation among key stakeholders, including owners, consultant or designing team, and contractors to ensure project completion time. With the concerted efforts of the project staff, the projects experience improved productivity early enough during construction, which in turn, subjugates the menace of errors, changes, and rework. It is, therefore, important for project owners to weigh their financial options before embarking on construction project to avoid any forms of financial problems. In course of the project execution, consultant should effectively oversee the design processes to avoid any ambiguities or complexities in project design that could make the design complicated for the contractor to implement. The consultant and contractor should also utilize quality equipment and materials in the design and construction. These would avert workers absenteeism and frequent equipment breakdown, thus enhancing work performance and productivity, minimizing design errors, change orders, and rework, and completing project on time. Cooperation and commitment of all key stakeholders in every step of construction brings gradual improvement of project performance and keeps project on schedule. The simulation results prove that the construction delay can be reduced in the long term through improvement of key construction delay factors and their associated items, such as technology accuracy, supervision personnel, experience of contractor, timely payment of staff, and timely decision of the project owner. The time lag in closing a project gradually reduces due to gradual improvement in handling the controlling factors of delay. This depicts the fact that better project performance, in terms of time, is a process that evolves over time in subsequent projects as delay factors are consistently being dealt with.

The five key delay factors, coupled with other criteria and endogenous variables embedded in the model interact with each other in a non-linear dynamical system, representing the complexities involved in project system, and conforming with the real-life situations for effective analysis in Thai construction industry. This study, through rigorous analyses, posits that technology accuracy in project design process, effective project supervisors and supervision, effective project management, experienced contractor, on-time staff payment, and owner’s timely decision in addressing pertinent issues during the project are effective policies that would effectively enhance better project performance and reduce project delay.

The DEMATEL-SD integrated system is useful in initiating panacea to other prevailing problems opposing performance in the construction sector. The model clearly showcases series of similar projects performed in succession, where steady decline is realized in the project delivery time and delay magnitude through consistent debasement of the threat of the key factors for each succeeding project. This explains the fact that developing subsequent effective measures against these time lag factors improves project performance gradually, as better project performance in terms of time is a phenomenon that evolves in succession of time. The developed dynamic model, which possesses flexible simulation capacities through the policy analyses, enhances practical project schedule management, as project stakeholders could easily examine influences of key factors on the project schedule. It also allows for the assessment of other project performance inhibiting factors mitigation measures in advance. Another merit of the developed dynamic model is that it helps project stakeholders to easily observe and analyze the effect of the occurrence of factors on the system behavior over time. This, in turn, enables stakeholders to identify key impact, and establish corresponding inhibiting measures, if necessary. Furthermore, the integrated model is easy and convenient for project personnel to apply in practical", as it is able to test with different scheduling scenarios to reflect real practices of the companies. Upper and lower bounds of the variables in the model, for example, technology accuracy, can be easily adjusted to test optimistic and pessimistic scenarios the company is facing. More delay factors may also be added into the developed dynamic model with some adjustment.

6.3 Contribution and Limitation

This study contributes to the "Thai construction industry. The DEMATEL-SD model is developed to analyze the problems of construction delay, showing the dynamics of delay controlling factors and their impacts on the project schedule over time. The controlling parameters of construction delay need adequate attention to reduce project time lag and subjugate the magnitude of construction project delay. Latest and integrated design technology should be adopted to repress errors in project design, which is in the early stage of construction. Accurate project design, coupled with a worthy number of supervisors and effective supervision, timely decision by the owner, experienced contractor, and effective project management are effective policies to be considered by Thai construction companies to improve project performance in terms of time in the construction and post-construction stages. The DEMATEL analysis results serve as a reliable mathematical decision criteria method to support SD modelling analysis, forming a hybrid system that can be used to effectively plan and manage project schedule in the long term. The study results help decision makers to better understand the uncertainties and complexities involved in construction projects through the convoluted relationships among delay controlling factors and hierarchical structure, and their impacts on project schedule to alleviate construction delay, thereby attenuating the threat of time and cost overruns, leading to better construction project performance in the long term.

This study focuses on construction projects in Thailand, which is an emerging economy having similar project environment and characteristics with other developing economies across the globe. The simulation model is premised on the intricating relationship system established through DEMATEL analysis which is designed by the exploration of opinions of 15 leading experts in the Thai construction sector. Therefore, more research spanning through other developing economies may be carried out with larger sample sizes. Initial values utilized in the DEMATEL-SD model development are from the DEMATEL analysis results and construction-related literatures that are not in particular Thai literatures. Also, the SD modeling approach may be conjugated or hybridized with other decision-making methods to initiate some model adjustment.

6.4 Recommendations and Future Studies

Since construction project delay is a menace associated with both emerging and developed economies, therefore, further investigations cutting across both economies could be conducted to advance the SD model and capture effective panacea to some other opposing problems of project scheduling and performance in the construction sector. Key delay factors used in this study are effective yet may be adjusted or added to suit with some real-life practices with different working cultures. For example, the uses of advanced technology on construction sites to enhance the work performance and reduce the construction delay may be investigated together with different workers' characteristics, such as educational background, work skill, and attitudes in technology adaptation to effectively plan for technology investment. Further study could also be performed to capture more insights of the key delay factors to effectively plan for delay reduction in the pre-construction, construction, and post-construction stages. Feedback of customers from previous projects could also be added into the SD model to improve the work performance from the pre-construction stage (e.g., enhancing two-way communication among the key parties, controlling the design quality, and utilizing a better design technology) to avoid and reduce the construction delay of the later projects. Also, delivering project within the scheduled budget is also an indicator of project performance. Therefore, the model could be modified to capture pertinent cost overrun variables in order to comprehensively explore the dynamics of the variables to establish effective policies that could be adopted to mitigate the menace of cost overrun as effective panacea to the monumental problem.

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APPENDIX

APPENDIX A
RESPONDENTS' DEMOGRAPHY

Total number of Respondents: 15			
Gender (%)	**Organization (%)**	**Job Title (%)**	**Working Experience (%)**
Male: 73	Contracting: 47	Project Manager: 27	5-10 years: 20
Female: 27	Consulting: 33	Quantity Surveyor: 13	10-15 years: 60
	Client: 20	Architect: 20	15-20 years: 13
		Others: 40	Greater than 20 years: 7

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Publications

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