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DYNAMICS OF PERTINENT PROJECT DELAY VARIABLES IN THE THAI CONSTRUCTION SECTOR: MATHEMATICAL ANALYSIS

BABATUNDE OLUWASEUN AJAYI
THANWADEE CHINDA

ABSTRACT

Project completion behind schedule is a struggle for the construction sector, affecting time, cost, and quality. This investigation has been necessitated by the lingering nature of project delay risks despite many extant analyses. This study collated expert opinions from the Thai construction sector on salient construction delay variables and their influence on each other for DEMATEL-SD analysis. The collated data were analysed and found consistent with a Cronbach's alpha of 0.939. Then, the DEMATEL technique was used to establish the influence weight of factors for the System dynamics (SD) analysis. It was discovered that minimising the design error at the preconstruction stage significantly reduces the magnitude of delay. Increasing values of design error and change order increase the rework profile. Besides, the project delivery within the scheduled 232 weeks can be ensured by minimising the threat of design error, design change, change order, rework, productivity problem, and by improving project management. This study adopted a hybrid mathematical system to holistically examine the construction delay risk by comprehensively exploring the dynamics of influencing variables and investigating their impact on the project scheme. The system helps project stakeholders to arrive at an effective decision in overcoming delay risks, thus minimising the cost overrun and improving the project quality.

KEY WORDS
construction delay, DEMATEL analysis, system dynamics, preconstruction, project management

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Babatunde Oluwaseun Ajayi

School of Management Technology,
Sirindhorn International
Institute of Technology,
Thammasat University, Thailand
ORCID 0000-0001-9691-1818

Corresponding author:
e-mail: babatunde.olu@dome.tu.ac.th

Thanwadee Chinda

School of Management Technology,
Sirindhorn International
Institute of Technology,
Thammasat University, Thailand
ORCID 0000-0001-7993-4313

INTRODUCTION

A construction scheme is an entire blueprint of when a project will be executed and the form of execution. The construction schedule, which is the backbone of any thriving construction project management, outlines project timeframes to keep everything on time. Project scheduling is established to keep the project on track, forecast problems, control costs, and enable timely project completion. Unfortunately, despite project scheduling arrange-

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ments, construction projects face the delay risk, which entails serious negative effects like disputes and total abandonment (Lonergan, 2018). Construction delays are a global phenomenon affecting national economies. Delays in construction project delivery, which is one of the biggest problems in construction management, remain a recurring phenomenon common in developed and emerging economies, often occurring from the design stage to the closeout stage (Carvalho et al., 2021; Jayaraman, 2021; Zhang, 2020). This extension in the time scheduled for project completion is usually a major loss to any construction project, and it decreases the country's GDP (Vishal & Myneni, 2021). Delays in construction project schemes result in time overruns leading to excess costs and, in turn, monetary losses. Time overrun, cost overrun, profit reduction, losses for the owner, distrust between the owner and the contractor, disputes between various stakeholders, and the total project abandonment are direct effects of delay (Salhi & Messaoudi, 2021; Anysz, 2019; Ametepey et al., 2017; Hassan et al., 2017). Therefore, time and cost overruns are common consequences of scheme delays (Kusakci et al., 2017; Sha et al., 2017; Khattri et al., 2016; Hamzah et al., 2011; Motaleb & Kishk, 2011; Pourrostam et al., 2011).

Many investigations have been conducted to identify the factors responsible for this monumental problem. For example, Timilsina et al. (2020) investigated delay causes in a Nepalese construction project, and Mizanur et al. (2014) studied the main causes for schedule delays in construction projects in Bangladesh. Al Amri and Perez (2020) investigated the causes of delays and cost overruns in construction projects in Oman. Many other studies focused on causative factors of delays (Ramli et al., 2021; Alsulaiti & Kerbache, 2020; Soumphonphakdy et al., 2020; Sohu et al., 2019; Saxena & Tomar, 2018; Kusakci et al., 2017; Rahman, 2018; Shahsavand et al., 2018; Soliman, 2017; Kesavan et al., 2017; Gonzalez et al., 2014; Hamzah et al., 2011; Motaleb & Kishk, 2011; Fugar & Baah, 2010; etc.). These investigations on construction delays highlighted scores of factors. Nevertheless, despite the identified factors, construction delays remain a persistent issue, buttressing the fact that an effective remedy to this monumental problem goes beyond the identification of factors, and there is a need for advance investigations in mitigating this problem. Therefore, this study aimed to mathematically examine the dynamics of the delay factors and their impact on the entire project time frame to facilitate effective decisions of project stakeholders, thus mitigating the risk of construction delay.

1. PREVIOUS STUDIES

The construction sector, which is an integral part of the country's economy, has been characterised by poor project performance due to project delays. A delay refers to the time extension to complete the project (Hamzah et al., 2011; Khaled et al., 2020; Masood et al., 2015). The project time extension is a common challenge and a global phenomenon that affects numerous projects in the construction sector (Kamandang & Casita, 2018; Tosniwal & Vanakudari, 2018; Vetrova et al., 2020; Jordão et al., 2020; Teplická et al., 2021). Construction delays are a common issue affecting the project duration, which is undesirable to project stakeholders (Asmitha, 2019). A project delay risk is associated with several factors relating to project complexities, which increase with the project size. Several such factors have been examined using different methods for ranking them in the order of criticality.

Anysz (2019) identified low productivity as a key factor inhibiting the timely execution of construction projects. Using the mean score analysis, Mydin et al. (2014) concluded that weather conditions, poor site conditions, poor management, incomplete documents, lack of experience, financial problems, contract modifications, delayed approvals, and coordination problems were the causes of delay. Meanwhile, Emuze (2018) used the mean score analysis and highlighted payment delays, slow decision-making by the owner, change orders, poor communication and coordination, and delays in approvals. Improper planning and scheduling, ineffective project control, management and supervision, poor design and delays in design, rework, shortage of skilled labour and difficulties in project financing were indicated by Saxena and Tomar (2018), who used the relative importance index in their analysis of critical causes of delay. As key delay categories particular to Iran, Zarei et al. (2018) named delays related to initial negotiations, delays related to the contracting process, and delays related to the planning process. The construction industry is large and volatile, and delays in construction projects are recognised as the most common, costly, and risky problem. Consequently, causes of delay were investigated by Qaytmas (2020). Insecurity, corruption, contractors' low experience, and poor management are among the leading causes of project delays in Afghanistan. Khahro and Memon (2018) adopted the relative importance index to conclude that slow material mobilisation, the unreliability of subcontractors, and labour and material shortages were the causes of delays in the construction industry. Given the frequency and severity of project delays, many studies researched the causes behind such problems, focusing on different countries and using different statistical approaches adopted for the factor rankings (Bounthipphasert et al., 2020; Paray & Kumar, 2020; Asegie, 2019; Chijindu, 2018; Nundwe & Mulenga, 2017; Seran et al., 2017; Seboru, 2015; Zen et al., 2008).

This study presents delay factors (Tab. 1) based on opinions of experts from the Thai construction industry and extant investigations on construction delay factors particular to developed and developing economies. The list reveals similarities between factors associated with the Thai construction sector and those frequently mentioned in the existing literature. It is important to note that 27 factors are direct causes (independent variables) of five embedded factors (dependent variables), namely, the design error, design change, change orders, rework, and productivity.

The decision-making process is essential in managing a successful organisation (Anastasiu, 2018). Decisions need to be made at all stages of a construction project, from the beginning, throughout the execution and to closeout stages (Szafranko, 2017). Various decision-making methods are applied in different situations; therefore, management of construction projects entails decision series. Strategy selection and implementation are important phases in the decision-making processes involved in construction projects. The four major approaches to a decision-making process are inductive, deductive, development of a benefit matrix, and marginal analysis (Szafranko, 2015).

These approaches differ from each other and can be used separately, in a sequence, or in conjunction with each other (Jajak et al., 2015). For example, Samani et al. (2012) examined the fuzzy systematic approach (i.e., fuzzy DEMATEL) to construction risk analysis, while Seker et al. (2017) examined the application of the fuzzy DEMATEL method for analysing occupational risks on construction projects. On the other hand, Erdogan et al. (2016) adopted the analytic hierarchy process as a decision-making tool for construction management. Anastaciu (2018) also investigated the decision-making process in construction project management using the ELECTRE I method.

The complexities of a construction project make the project system difficult. Pertinent factors embedded in the implementation process make the construction project extremely complex, causing colossal challenges to the project control and debasing performance. A hierarchical listing of key factors and the cause–effect relationships among them may not be adequate for the holistic investigation of a construction delay.

Having established the influence weight of these factors, it is also important to comprehensively explore the dynamics of these factors to establish their impact on the entire project schedule for effective decision and planning to significantly mitigate the risk of a construction project delay.

According to Yu-jing (2012), system dynamics (SD) modelling is an effective way to improve performance through effective project control. Researchers have been advocating for exploring nonlinear and dynamic complexity issues involved in construction management. For instance, Maryani et al. (2015) examined the SD approach for modelling construction accidents. SD modelling involves the integration of methods, combining network analysis, fuzzy logic analysis, discrete event simulation, and agent-based simulation.

It is used in examining the impact of a complicated contextual condition in project planning and control, effectiveness and performance, strategic management and sustainability (Liu et al., 2019). The SD's role in advancing other decision-making methods to comprehensively explore relationships and dynamics of a system cannot be overemphasised, as it provides grounds for establishing the impact of parameters on a set standard, initiating effective decision-making to enhance better project performance.

It is important to mention that many investigations have contributed to identifying the causes of delay, but the dynamics and impact of the factors have been rarely explored. Many previous studies have been solely based on a statistical approach to ranking factors in the order of criticality. Usually, researchers opt for such statistical tools as the relative importance index, frequency analysis, average index, linear regression and factor analysis.

Therefore, a hybridisation and combination of mathematical decision-making tools to unravel the dynamics and impact of these factors on project schedules have been rarely investigated. Hence, the need for this study, which adopts a novel approach to identifying key delay factors exploring the dynamics

Tab. 1. Key factors affecting construction delay

Independent variable (cause)	Dependent variable (effect)	Country of study	Reference
• Poor communication • Consultant's lack of experience • Technology used	Design error (DE)	Iran, Malaysia, Norway, Portugal	Abbasi et al. (2020), Arantes & Ferreira (2020), Zidane & Andersen (2018), Fuadie et al. (2017), Shamsudeen & Obaju (2016), Najafabadi & Pimplikar (2013), Couto (2012), Love et al. (2012), Suther (1998)
• Shortage of materials • Owner's late decision	Design change (DC)	Egypt, Ethiopia, Iran, Jordan, Malaysia, New Zealand, Nigeria, Norway, Portugal, Saudi Arabia, Turkey, USA	Bassa et al. (2019), Eksander (2018), Zidane & Andersen (2018), Gebrehiwet & Luo (2017), Lessing et al. (2017), Tafazzoli & Shrestha (2017), Suleiman & Luvara (2016), Samarah & Bekr (2016), Arantes et al. (2015), Yana et al. (2018), Memon (2014), Owolabi et al. (2014), Aziz (2013), Najafabadi & Pimplikar (2013), Kazaz et al. (2012), Mirshekarlou (2012), Sun & Meng (2009)
• Lack of sufficient data before the design • Owner's lack of experience • Inadequate planning and scheduling • Mistake in producing design documents • Rigidity of the consultant • Complexity in project design • Owner's change in requirements • Late procurement • Improper construction method used by the contractor • Difficulties in project financing • Change in materials type during the construction • Owner's financial problem • Delayed payment	Change order (CO)	Denmark, Egypt, India, Iran, Jordan, New Zealand, Nigeria, Norway, Finland, Portugal, Thailand, UK, USA	Abbasi et al. (2020), Arantes & Ferreira (2020), Bahra (2019), Jusilla & Lahtinen (2019), Khoso et al. (2019), Mittal & Paul (2018), Shahsavand (2018), Zidane & Andersen (2018), Lessing et al. (2017), Tafazzoli et al. (2017), Samarah & Bekr (2016), Larsen et al. (2016), Alaryan et al. (2014), Aziz (2013), Halwatura & Ranasinghe (2013), Najafabadi & Pimplikar (2013), Al-Hams (2010), Keane et al. (2010), Toor & Ogunlana (2008), Aibinu & Odeyinka (2006), Ahmed et al. (2003)
• Poor supervision • Poor project management	Rework (R)	Egypt, Ethiopia, Iran, Jordan, Portugal	Arantes & Ferreira (2020), Mahamid (2020), Chandrusha & Basha (2017), Enhassi et al. (2017), Gebrehiwet & Luo (2017), Abeku et al. (2016), Mahamid (2016), Samarah & Bekr (2016), Alavifar & Motamedi (2014), Aziz (2013), Love & Smith (2003)
• Frequent equipment breakdown • Shortage of skilled workers • Poor quality of materials • Conflicts between contractors and parties • Workers' absenteeism • Late arrival of materials/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 & Rao (2018), Zidane & Anderson (2018), Lessing et al. (2017), Moradi et al. (2017), Gascuene et al. (2014), Hickson & Ellis (2014), Aziz (2013), Desai & Bhatt (2013), Kazaz et al. (2012), Ameh & Osebo (2011), Sullivan & Harris (1986)

of the factors to investigate their impact on the project scheme using DEMATEL and system dynamics (DEMATEL-SD). DEMATEL, as a decision-making method, is the proposed fundamental method which will be used as input in the SD model build-up.

2. Research methodology

This investigation develops a conceptual framework, hypothesising that construction delay is mainly caused by five key (direct) factors (or dependent variables), namely, the design error (DE), design change (DC), change order (CO), rework (R) and productivity (P). Each factor is associated with several independent variables (Tab. 1). Interview questions are developed with five delay factors to collect the data for the DEMATEL-SD analysis. The DEMATEL method is then used to establish the influence weight of factors for the SD simulation model to investigate the impact of each factor on the project scheme through the delay factors dynamics.

2.1. Data collection

The five key construction delay factors and their associated items were used to develop the interview questions to collate information for the DEMATEL-SD analysis. The introductory part of the interview requested respondents to provide their background information, including their current organisation, position, and experience in the construction industry. The main part was designed to collate information about the degree of influence between the five delay factors.

The experts (respondents) were asked to rate the degree of influence (the impact) of one factor in respect of the other on a scale from 0 to 4, where 0 represented "no influence" and 4 meant "very high influence" (Kaushik & Somvir, 2015; Si et al., 2018; Hossain et al., 2020). This was done through binary comparison, where one factor was compared to another factor. As an example, one question asked, "What is the degree of influence between factor DE and factor CO". The response with the value of 4 ("very high influence") showed that the factor DE had a tremendous impact on CO in causing construction delays. The designed questionnaire was reviewed by a group of qualified experts to validate its content.

The DEMATEL analysis is not based on the sample size but on expert judgements, drawing on their substantial experience in the industry of concern (Hossain et al., 2020). In this study, data for the analyses were provided by 15 leading experts working in the building construction companies in Bangkok and other provinces of Thailand. This number of experts was considered adequate (Susanty et al., 2019; Kolbel et al., 2017; Mohiuddin et al., 2017; Yadav et al., 2016; Tsai et al., 2016). The experts were project managers, project engineers and experienced operators with a significant level of work experience in large building construction with an average of THB 100 million in capital investment and over 100 operators. They were also involved in several decision-making efforts related to construction delays.

2.2. DEMATEL analysis method

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis was developed to resolve complicated, problematic groups using matrix mixtures (Kakha et al., 2019; Shieh et al., 2010; Wu et al., 2010). Structured models allow for effective evaluation and formulation of cause and effect relationships. They are described as an effective method for designers and decision-makers, especially in the management field (Kaushik & Somvir, 2015). The approach has been widely applied in many areas, such as airline safety management, web advertising, 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). One of the advantages of this method is the ability to visualise the interrelationships between factors and enable the decision-maker to clearly understand which factors have a mutual influence on one another (Si et al., 2018).

2.3. System dynamics modelling approach

The resulting causal diagram of the DEMATEL analysis is used as a basis for the SD modelling analysis. System dynamics (SD) modelling was created at the Massachusetts Institute of Technology (MIT) by computer pioneer Jay Forrester in the mid-1950s for modelling and analysing the behaviour of complex systems in industrial contexts (Boateng et al., 2012). It was designed to help decision-makers learn about the structure and dynamics of complex systems. The system dynamics approach is based on the concept of a causal loop diagram and is effective in modelling processes that involve change over time and the feedback concept (the transmission and receipt of information) (Ogunlana, 2003).

A clear understanding of how system parts interact with one another and how a change in one variable affects the other over time is the core of system dynamics. Each causal link is assigned a polarity, either positive (+) or negative (-), to indicate how a variable impacts on or is impacted by the other over time (Sterman, 2000). Based on Kim (1999,) 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 (-) signs. If there are no negative (-) signs or an even number of negative (-) signs, then the loop is reinforcing. Contrary, the loop is balancing if there is an odd number of negative (-) signs. 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 signify the rate of change in the system 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 as Eq. 1.

$$Stock(t) = \int_{to}^{t}[Inflow(s) - Outflow(s)]ds + Stock(t_o) \quad (1)$$

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, while $Inflow(s)$ and $Outflow(s)$ represent the information going in 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. 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 stock is as shown in Eq. 2.

$$Net\ flow = \frac{dS}{dt} = f(S,t) \quad (2)$$

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

3. DEMATEL analysis results

Data were collected from experts. Cronbach's alpha (SAS 2007) was adopted to check the internal consistency of the data. It was calculated based on Eq. 3 using MS Excel and the SPSS 23 software, where k is the total number of delay factors, $\sigma^2_{Y_i}$ is the variance variance for the sum of all respondents. The results revealed that the expert judgements used in the DEMATEL-SD analysis are highly reliable, with Cronbach's alpha of 0.939, which is greater than a minimum acceptable value of 0.7 (SAS, 2007).

$$(\alpha) = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k}\sigma^2_{Y_i}}{\sigma^2_X}\right) \quad (3)$$

Among 15 respondents, 73 % were male. The experts worked for contractors, consultants, and clients of building construction projects, respectively representing 47 %, 33 %, and 20 % of total respondents. Furthermore, 40 % of them were engineers, 27 % worked as project managers, 20 % were architects, and 13 % were quantity surveyors in large construction projects. More than 80 % of respondents had at least ten years of work experience in the construction industry and their current organisations. Respondents' work experiences and their roles in construction projects proved their suitability to provide data for the DEMATEL-SD analysis.

The collected data was analysed using DEMATEL and the MATLAB 2019 software. The following analysis results were discerned.

- Step 1: Compute the direct-relation matrix A. The direct-relation matrix A of all 15 experts was calculated, as shown in Eqs. 4 and 5, and Tab. 2.

$$A = [a_{ij}] = \frac{1}{H}\sum_{k=1}^{H} z_{ij}^{k} \quad (4)$$

$$S = max_{1\le i\le n}\sum_{j=1}^{n} a_{ij} \quad (5)$$

- Step 2: Normalise the direct relation matrix A. The normalised initial direct-relation matrix D is constructed as shown in Eq. 6 and Tab. 3.

$$D = \frac{A}{S} \quad (6)$$

- Step 3: Compute the total-relation matrix (T). The total-relation matrix T is calculated, as described in Eqs. 7-9 and Tab. 4.

$$T = [t_{ij}]_{nxn} = D(I - D)^{-1} \quad (7)$$

$$R = [(\sum_{j=1}^{n} t_{ij})]_{n\times 1} = [t_i]_{nx1} \quad (8)$$

$$C = [(\sum_{i=1}^{n} t_{ij})]_{1\times n} = [t_j]_{1xn} \quad (9)$$

Tab. 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	2.333	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

Tab. 3. Matrix D calculation

D					
	DE	DC	CO	R	P
DE	0	2.2394	0.2465	0.2535	0.2324
DC	0.2465	0	0.2183	0.2324	0.2254
CO	0.2394	0.2324	0	0.2394	0.2676
R	0.2606	0.2465	0.2465	0	0.2465
P	0.2254	0.2254	0.2394	0.2606	0

Tab. 4. Matrix T and the calculation of the sum of rows (R) and the sum of columns (C)

T						Ri
	DE	DC	CO	R	P	
DE	5.4310	5.4966	5.5346	5.6969	5.6188	27.7779
DC	5.4031	5.0831	5.2944	5.4551	5.3883	26.6240
CO	5.6525	5.5199	5.3652	5.7173	5.6705	27.9254
R	5.7624	5.6223	5.6571	5.6210	5.7525	28.4153
P	5.5223	5.3969	5.4389	5.6078	5.3376	27.3035
Ci	27.7713	27.1188	27.2902	28.0981	27.7677	

Tab. 5. Prominence, relation, and the order of influence of construction delay factors

Factors	Prominence (Ri+Ci)	Rank of factors	Relation (Ri-Ci)	Cause/Effect group
Rework (R)	56.5010	1	0.3180	Cause
Design error (DE)	55.5365	2	0.0077	Cause
Change order (CO)	55.2049	3	0.6355	Cause
Productivity (P)	55.0578	4	-0.4630	Effect
Design change (DC)	53.7306	5	-0.4982	Effect

Tab. 6. Total degree to which a factor is influenced by other factors

RANK	FACTOR	VALUE (%)
1	Rework	20.4691
2	Design error	20.1197
3	Change order	19.9995
4	Productivity	19.9463
5	Design change	19.4654

Tab. 7. 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

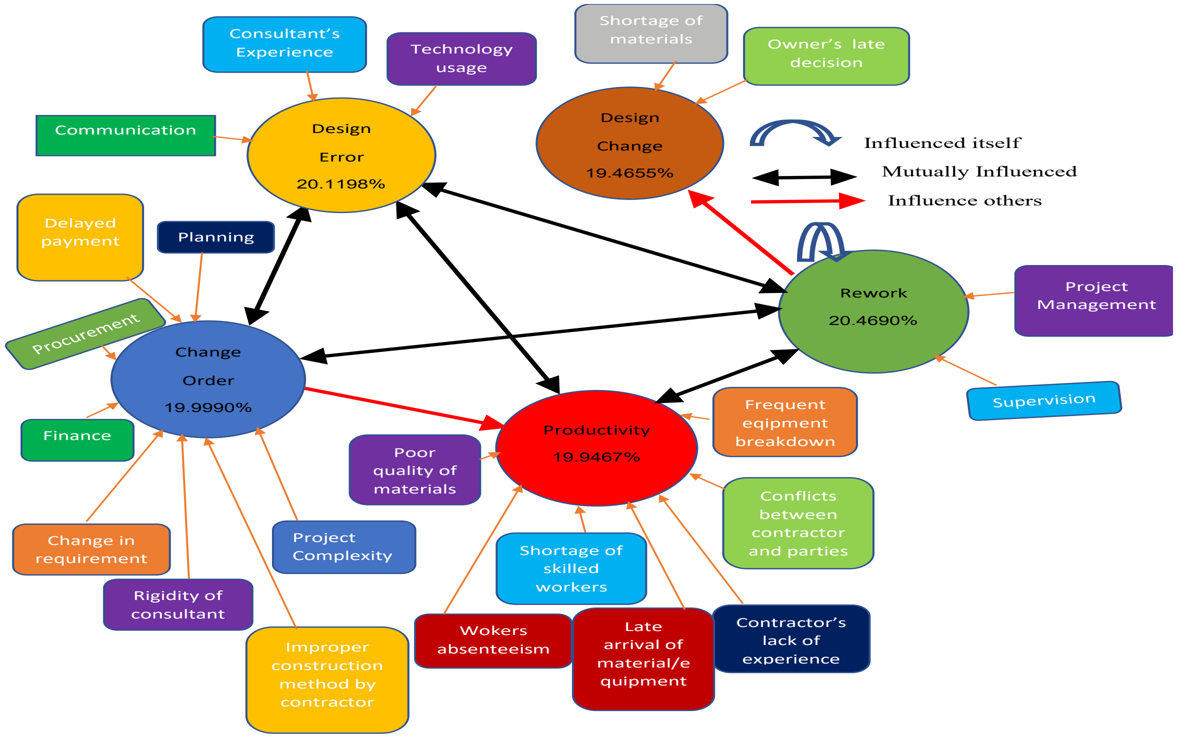

Fig. 1. Summary of DEMATEL analysis results

- Step 4: The prominence and relation of the total-relation matrix T are computed. The vectors (Ri+Ci) and (Ri-Ci) are shown in Tab. 5.
- Step 5: The total degree to which a factor is influenced by the other factor is established by the ratio of each prominence value to the summation of all prominence values (Tab. 6).
- Step 6: Select a threshold value (α) to obtain the diagraph (see Eq. 10). In this study, the threshold value (α) is calculated as

$$\frac{5.4310 + 5.4966 + 5.5346 + \ldots 5.3376}{25} = 5.5218$$

According to Rezahoseini et al. (2019), it is important to form the Matrix F setting element Tij in Table 4 that is equal to or bigger than the threshold (α) of the matrix T to 1 and element Tij in Tab. 4 that is less than the threshold (α) of matrix T to 0. The matrix F for α=5.5218 is calculated, as shown in Tab. 7. The matrix F is used to construct the DEMATEL digraph (Fig. 1). The DEMATEL digraph shows that the design error (DE) factor has a mutual influence 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), on the other hand, has a mutual influence with the design error (DE), change order (CO), and productivity (P) factors, and it also influences itself.

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} [t_{ij}]}{N} \tag{10}$$

4. SD MODELLING RESULTS

4.1. SD MODEL OF CONSTRUCTION DELAY

The five key construction delay factors, the influencing characteristics (Fig. 1) of which were established by the DEMATEL analysis, spanned across the project stages. It is noteworthy that a design error was a problem in the preconstruction stage, according to this study. In a typical design-bid-build system, the design process is completed before the bidding process starts, after which the construction and postconstruction processes commence. The key stakeholders involved in the preconstruction stage were the owner and consultant. The design change, change order, rework, and productivity were problems encountered during subsequent project stages as the contractor was actively involved in this stage with the support of the owner and the consultant to monitor the project. Productivity was also an issue in the postconstruction stage. Therefore, there was a need for proper management and supervision to keep up the productivity to conclude the project on time. The model describing the workflow of the project was established. Fig. 2 describes the workflow of the process (simulation model), while Fig. 3 describes the conceptual model explored to establish the simulation model.

The design process model, which was built on three important concepts, is an embedded and complex system of staff, the productivity in the course of the design process, and their communication overhead. The more people the project involves, the bigger the communication overhead is generated. The design development rate is a function of productivity in design, the number of staff and communication (Eq. 11).

$$\begin{gathered} Design\ development\ rate = productivity\ * \\ *\left(1 - \frac{communication}{100}\right) * staff \end{gathered} \tag{11}$$

The variable Effective Designers (Eq. 12) depicts the number of full-time, experienced staff that can work on the design. New staff (designers) was believed to have 80 % productivity, subjected to improvement by experienced staff (Suslov & Katalevsky, 2019)

$$\begin{gathered} Effective\ Designers = 0.8 * New\ Designers\ + \\ +(Experienced\ Designers\ - \\ -Experienced\ personnel\ needed\ for\ training) \end{gathered} \tag{12}$$

Design tasks were assigned among three different groups of designers with two possible outcomes, i.e., the design was either completed correctly or not, which depended on the error proneness of the designer. The design error proneness by expert designers was given as 10 % of tasks, designers with experience in other projects was 20 % of tasks, and newly recruited designers was 25 % of tasks (Love et al., 2008).

This study considered a design process consisting of 996 requirement units (tasks to be completed). The process scheduled to be completed within 23 weeks (162 days) was a function of several enhancing parameters. The "new designer" and "experienced designer" stocks were associated with two flows representing the rate at which new designers were added and their assimilation. These depended on the number of new designers (staff), as it was hypothesised that the new staff became experienced after 30 days of work. The design process was scheduled to be concluded with a budgeted cost of THB 16,861,960 and an average salary of THB 30,770. Suffice it to mention that the DEMATEL-SD model was applied to an infrastructural project scheduled to be completed within 232 weeks, with 23 weeks for the preconstruction stage, 200 weeks for construction and 9 weeks for closure. The planned project tasks consisted of 10,000 units (Wang et al., 2017). The preconstruction stage consisted of 996 units of tasks, while the construction and postconstruction (closure) stage consisted of 9004 units of tasks.

A group of experts working in leading construction companies in Bangkok and other provinces in Thailand participated in the model validation process. They were top executives, owners, and engineers with

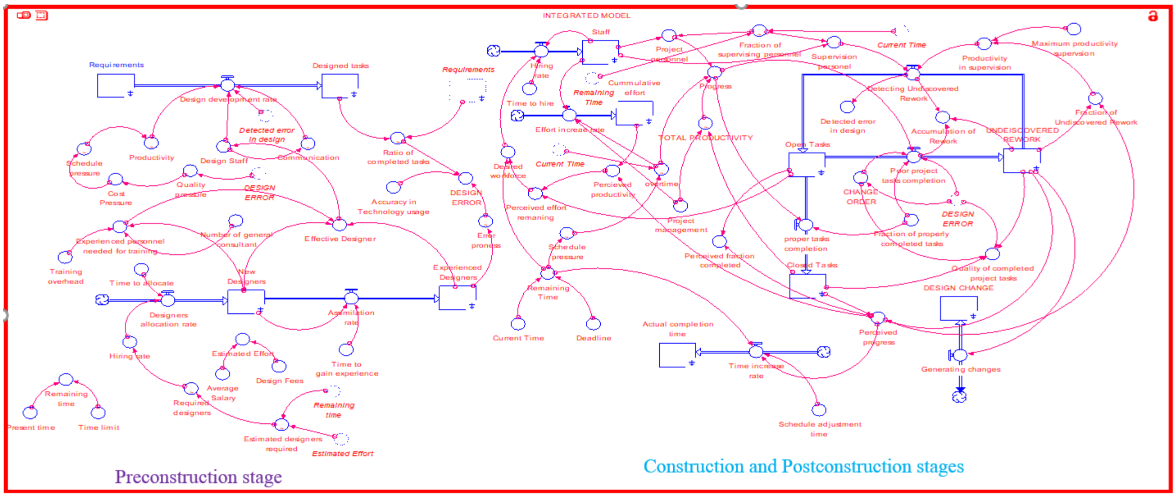

Fig. 2. SD model of construction delay

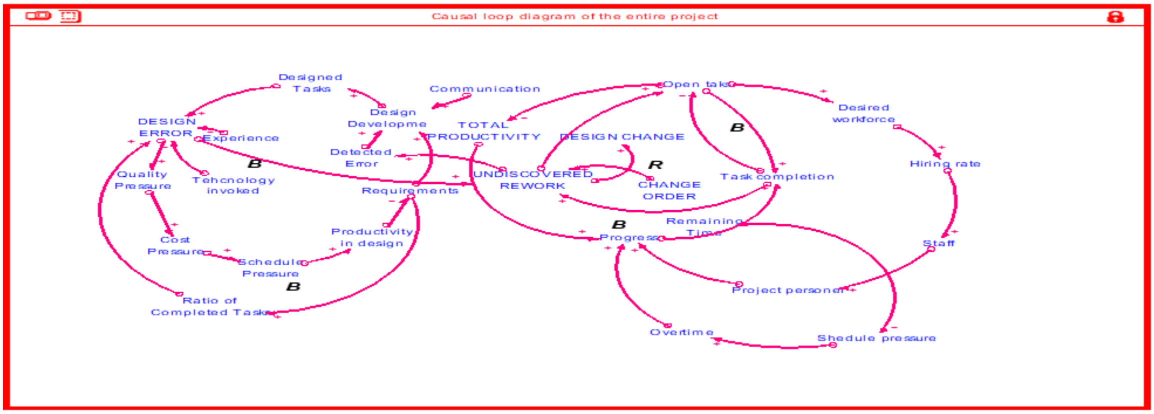

Fig. 3. Causal relationships among key construction delay factors

more than 20 years of work experience in large building construction with an average of THB 100 million in capital investments and over 100 operators. Preliminary information was shared explaining how the model was developed. This helped the experts understand how the model worked. Experts were asked to review the model and suggest improvements. The model was subsequently adjusted based on their recommendations and comments.

4.2. SIMULATION RESULTS

Data from the DEMATEL analysis results are used in the SD model of construction delay (see Tab. 8). Communication, experience, and technology influenced the design error. Design error was, therefore, minimised by these three sub-criteria from 0.2 to 0.0047.

The maximum value of technology accuracy could not be 1 (i.e., 100 %) since human activities could not be 100 % void of error, especially when it comes to the design process, no matter the level of expertise exhibited in handling an advanced engineering design (software) technological system. Even if systems can operate without human intervention, the chance of error still exists (Foord & Gulland, 2006; Busby, 2001). The initial value of design error based on DEMATEL was 0.2, while the minimised value was 0.0047.

Fig. 4 depicts the actual project completion time for different values of the design error. Line 1 (blue) shows the design error at 0.0047, line 2 (red) represents the design error at 0.1, while line 3 (purple) represents the design error at 0.2 (the base value). With the minimised value of the design error (0.0047), the construction process would be completed in the 217th week (and the entire project would be completed in the 240th week).

If the design error is 0.1, it will take 221 weeks to be concluded (amounting to 244 weeks for the entire project). It would take 225 weeks to complete the construction and postconstruction processes if the

VARIABLE	VALUE	SOURCE
Technology accuracy	0.03-0.07	DEMATEL analysis results
Change order	0.1-0.2	DEMATEL analysis results
Design change	0.194	DEMATEL analysis results
Design error	0.0047-0.2	DEMATEL analysis results
Rework	0.2	DEMATEL analysis results
Project management	0.1	DEMATEL analysis results
New designers	4	Suslov & Katalevsky (2019)
Fraction of properly completed tasks	0.6	Ogano (2016)

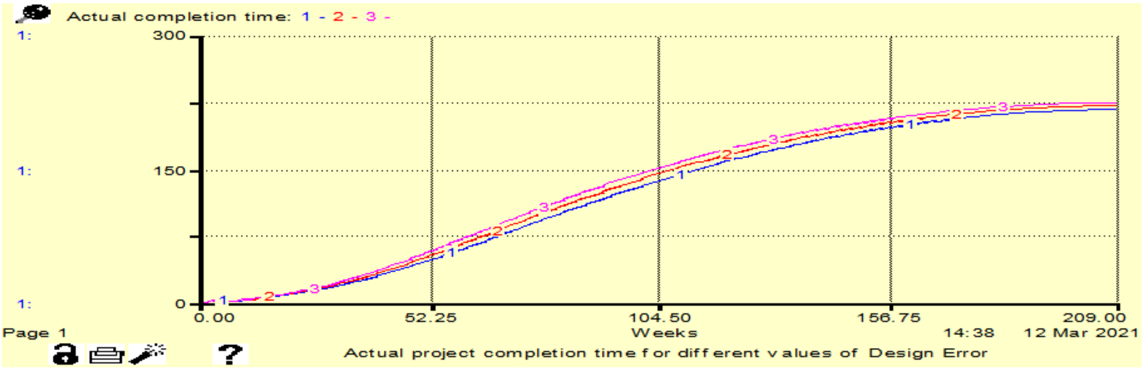

Fig. 4. Actual completion time when Design Error values are 0.0047, 0.1, and 0.2, respectively

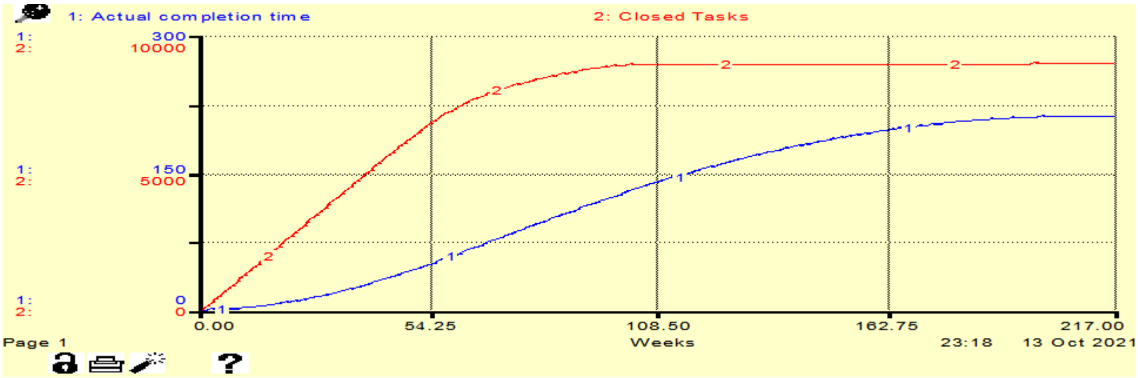

Fig. 5. Actual project completion time versus closed tasks

design error value was 0.2, amounting to 248 weeks for the entire project to be concluded.

Fig. 5 shows that construction and postconstruction are closed at the 217th week (8 weeks later than the stipulated time). This is a justification for minimising the design error, which is a problem of the preconstruction stage. This underscores the fact that construction delays are a risk that originates at an early project stage. Unlike many previous investigations, this study focuses on the need to mitigate the risk of the design error to minimise a project delay. The consultant's role is crucial in ensuring proper supervision of the design process to avoid errors.

The combined effect of the design error and change order on the project schedule contributes to the effect of rework on the project schedule. Based on the DEMATEL digraph of factors, rework is seen as the most prominent factor. The SD model, premised in this scenario as rework, is impacted by the change order, design error and productivity. This makes

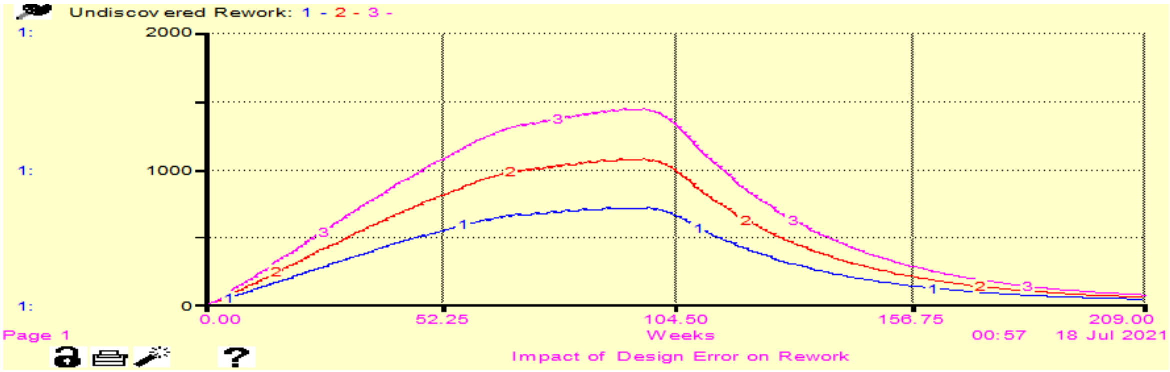

Fig. 6. Impact of the Design Error on Rework when the Design Error values are 0.0047, 0.1, and 0.2, respectively

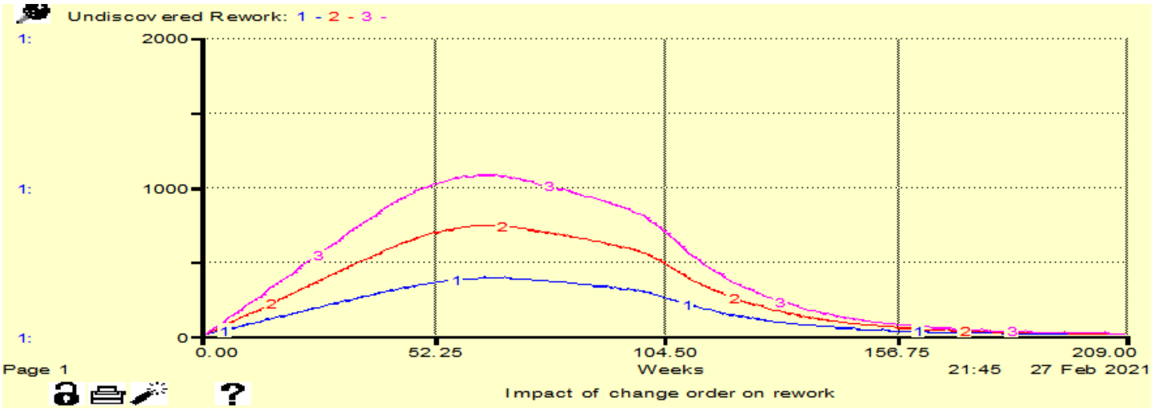

Fig. 7. Impact of the Change Order on Rework when the Change Order values are 0.1, 0.2, and 0.3, respectively

rework a central factor in the model influenced by others as it is described by a stock. Fig. 6 depicts the increasing effect of the design error on rework. Project reworks rise to 1450 units of tasks when the design error is 0.2 (line 3), while rework is minimal when the design error is 0.0047 (line 1). This result explains the linear relationship between the design error and rework, which also corroborates the findings by Love et al. (2008), stating that the design error contributes greatly to the total amount of rework experienced in a construction project which later results in a schedule delay. On the other hand, an increasing value of change order increases the magnitude of rework (Fig. 7). Some changes were made at an early stage of construction, thereby enhancing high rework at the stage, but later, in the course of the project, supervision became more effective, and tasks were completed according to the owner's specification, thereby reducing the threat of rework along the line.

The early stage of construction faces many problems ranging from the design error, change orders, productivity in supervision, the inability of staff to adapt to the construction process on time and others, thereby resulting in many poorly completed tasks which account for a high magnitude of rework even up till the mediate stage of construction. But as the project continues, workers adapt to the work process, and this increases the rate of properly completed tasks and reduces the amount of poorly completed tasks, which, in turn, reduces the rework drastically. This explains the parabolic nature of the rework curve (Fig. 8). The threat of rework was drastically mitigated at the construction stage, thereby leaving the post-construction stage with fewer problems. A serious complication in the post-construction stage would complicate the work cycle and result in a serious project delay. This corroborates the DEMATEL value of rework, showing that rework should be treated seriously and aptly and be made as minimal as possible (say, 0.2) to finish the construction project on time. Fig. 8 shows the rework, closed tasks, and completion time profiles under the combined influence of design error, change order, and productivity.

Fig. 9 depicts the rework profile versus cumulative effort and the actual completion time. The cumulative effort steadily increases throughout the construction process, necessitating a timely clamp-

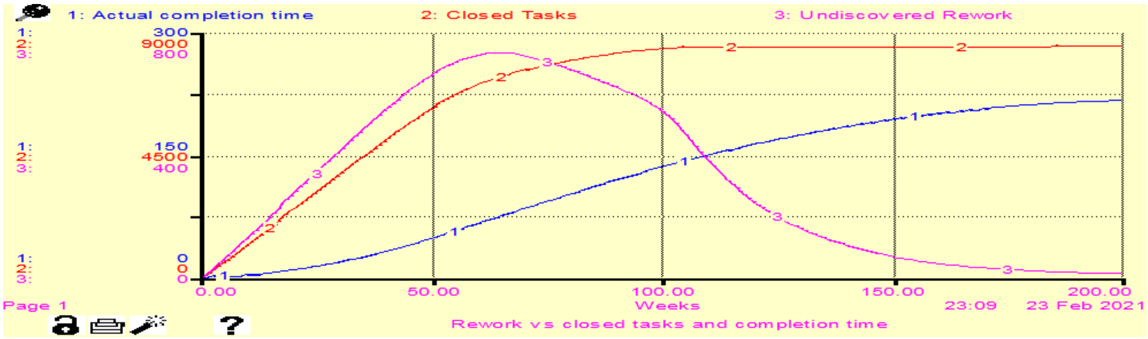

Fig. 8. Relationships among Rework, closed tasks, and completion time

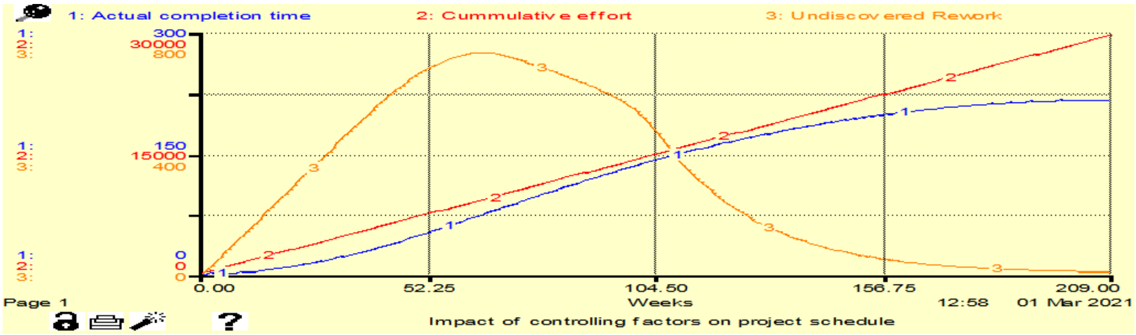

Fig. 9. Actual completion time with the cumulative effort and undiscovered rework

down of rework to ensure the whole process is concluded on time.

Usually, the postconstruction stage is not given the needed attention by project stakeholders, which makes the project suffer delays even at this stage. Therefore, closing more tasks at this stage demands improved productivity. So far, the dynamics of the delay factors and their impact on the project schedule have been examined. Construction delays are minimised, especially with the mitigation of design error and a minimal base value of the change order, which debase the threat of rework and allow for improved productivity. Even under such circumstances, it took 240 weeks to close the project instead of the initially planned 232 weeks, though it could have taken 248 weeks to conclude it, which is much later than scheduled. This analysis is based on the default value of project management of 0.1. According to Ogano (2016), project management can be improved for better project performance in terms of time, say $P \leq 1$. According to this study, project management is a factor associated with rework and based on the prominence value of rework of 0.57, project management is bound and can take a value within 0 and 0.57, which is still less than unity. The studied construction project could be completed within the budgeted 232 weeks if a better project management system was adopted (say $P=0.53$). It would require a magnificent level of expertise and commitment from the consultant to achieve this.

Fig. 11 depicts the actual completion time profiles for different levels of project management from 0.1 to 0.53. The construction project is concluded in the 232nd week as scheduled, with the project management value of 0.53. The lower the value of project management, the greater the time lag in completing the project. Hence the need for careful consideration of the prominent delay variables hinged on improved project management for timely delivery of a construction project. Project management is crucial in determining the project progress during construction (Ogano, 2016). Procurement and construction are considered the major stages of project management. The procurement system determines the availability of quality materials, their effective use, and the facilitation of reliable and robust construction processes (Matheu, 2005). Effective project management ensures that project members are assigned to specific tasks and that effective monitoring of project progress is performed (Purdue University, 2021). The results, as shown in Fig. 11, prove that an increasing value of project management reduces the project time lag. With better project management, tasks are assigned to project stakeholders without bias and prejudice, thus allowing for effective monitoring of the work progress and, finally, reducing the construction delay.

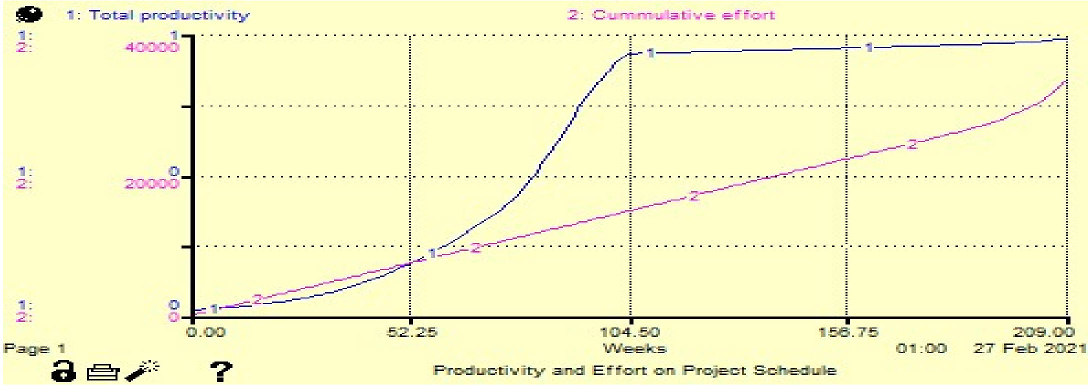

Fig. 10 Total productivity with the cumulative effort

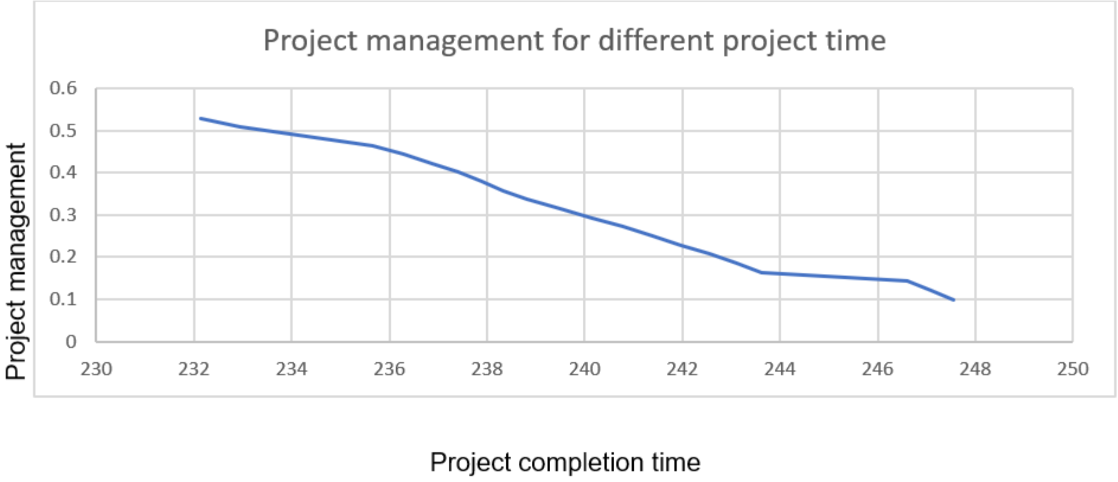

Fig. 11. Actual completion time for different values of project management

5. Discussion of the results

This study adopted the system dynamics modelling to explore the dynamics of factors and the impact of the controlling factors on the project schedule. Effective communication, experience, and better technology are used to reduce the magnitude of the design error. This explains the importance of technology use and communication flows among staff and experience in the design process. The existing advanced design software demands a high level of expertise and experience in applying it to project designs. Effective engineering design software is crucial in modern construction work. Rhino 3D, Revit Architecture, Sketchup, V-Ray, ArchiCAD, Grasshopper, Dynamo, and Fusion 360 are examples of such design software (Archistar, 2020). The performance and accuracy of the design process depend on the effectiveness of handling this software. Some of it is standalone (i.e., it 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 to a technology accuracy of 0.03, and the integration of two or more pieces of software corresponds to higher values of the technology accuracy. Therefore, it is important that designers undergo training in design technology to ensure the effective use and enhance design accuracy. Technical know-how (i.e., technology use) and experience are interrelated 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 designer capabilities to achieve better project performance and minimise delays at the beginning of the projects.

The design error has a direct relationship with rework, thereby contributing significantly to a schedule delay. Whenever there is an adjustment in design during construction, some completed tasks might need to be redone, which enhances rework in the process. On the other hand, change order varies directly as rework (increasing the value of change order increases the value of rework), changes during construction alter the initial scope of work, and this modification or alterations necessitates reworks as some completed tasks must be redone. Therefore, it is imperative for project stakeholders to ensure that project scope and requirements are clearly spelt out at the early stage of the project to avoid or mitigate the threat of change order during construction. The impact of the design error on the entire project schedule was examined.

The project ended in the 240th week with the minimised value design error. It could have taken longer to close the project if the design error was not minimised at the preconstruction stage. In addition, closing more tasks demands a high level of productivity as an enhancement for the timely completion of the project. The design process was completed with an error as low as 0.0047, which is less than the initial value established by DEMATEL, signifying that for a project design to be classified as a design with a reasonable level of accuracy, the design error quantity should not be greater than 0.2 (i.e., Design Error ≤ 0.2) or else the project will suffer serious delays because the design is error bound and characterised by a colossal inaccuracy.

The project extension would be longer if the error in the design is greater than 0.2, as many tasks would have to be reworked. This underscores the importance of the design process with a reasonable level of accuracy. A similar policy applies to change order, as explained by the impact of a change order on rework. The change order has a direct relationship with the actual completion time through rework. The more changes made during construction, the more the rework, which affects the project completion time. The total productivity is modelled to depend on project management as the productivity problem is also a management issue (Rojas & Aramvareekul, 2003; Ogano, 2016).

The project converges with a productivity of 0.8, as shown in Fig. 10. This agrees with the conclusion by Ogano (2016), stressing that a project can be almost concluded with a productivity of around 80 %, a productivity of 20% at 0% of remaining tasks. This also validates the result established by DEMATEL, attributing an influence weight of 0.199 to productivity. The project can be delivered at the stipulated time by carefully considering the pertinent delay factors accompanied by improvement in project management.

CONCLUSIONS

This study adopted a novel approach to the analysis of construction delay risks. DEMATEL-SD was adopted to investigate the dynamics of the controlling factors of delay. The hybrid system demands to collect expert opinions on the level of influence of one factor on the other via a binary comparison for the DEMATEL-SD analysis. A conclusion can be drawn that minimising the risk of design error, design change, change order and rework minimises the schedule delay. Therefore, project stakeholders should work consistently to mitigate the threat of these controlling parameters to facilitate improved productivity and minimise the problem of delay.

Companies should give adequate attention to the design process to ensure the project design is void of colossal errors. Consequently, they should invest more in technology, select experienced design teams and encourage effective communication to easily minimise the magnitude of rework and changes during construction as a pathway to improving productivity and quality. Also, good quality of project management is imperative as it enhances timely detection of rework and improves productivity.

This study contributes to the body of knowledge through the uses of DEMATEL-SD to analyse the problem of construction delay and the SD modelling to show the dynamics of delay-controlling factors. The SD analysis is divulged in this study as a reliable mathematical decision criteria method to advance the DEMATEL technique, which underscores the fact that the DEMATEL analysis is a reliable tool to initiate other decision-making methods, especially when there is a need to adopt a hybrid system. The project design process and outcome are key determinants of the overall project performance.

Therefore, the project owner and consultant must work together effectively to achieve a reasonable level of accuracy in the project design and avert problem-bound construction and postconstruction processes. This study helps decision-makers to better understand the complexities involved in construction projects through the comprehensive dynamics of delay factors as a modus operandi to alleviate construction delay. The dynamic model can be modified and used as an effective tool to capture and proffer solutions to several other besetting problems in the construction sector.

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