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INTEGRATION OF LEAN SIX SIGMA INTO EARNED VALUE MANAGEMENT USING SYSTEM DYNAMICS

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Abstract. A Few Lean Six Sigma (LSS) papers were studied during the construction project's progress. This study proposes the integration of LSS, system dynamics (SD), and earned value management (EVM) as a comprehensive toolkit for data-driven decision-making. Significant waste- and quality-related interdependencies were identified using DEMATEL techniques with 27 Saudi construction experts. SD with two interdependent models of waste causes (WCs) and quality causes (QCs) were utilized to assess the project's performance. Two metrics were employed: the sigma rating and the value-added ratio in the EVM generated by the developed SD model. The findings indicated that eliminating WCs had little impact on enhancing the project performance in the early stages of the project. The impact increased with the progress of the project. The improvement of the project quality was minimal for "increases of errors and omissions in design documents" and maximum for "increasing morale and attitude affect the quality of the project".

Keywords: system dynamics, earned value management, sigma rating, waste cause, quality cause, causal loop diagram.

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1. Introduction

Waste (non-value-added activities) and poor quality in construction projects can significantly harm performance. They lead to cost overruns and schedule delays. A study by the Construction Industry Institute in the United States indicated that poor quality and rework can account for 2.4% to 12.4% of the total project cost (Karimi et al., 2018). In addition, The National Institute of Standards and Technology (NIST) in the United States estimated that rework and poor quality can result in schedule delays of 10% to 30% (Forbes & Ahmed, 2020).

Lean Six Sigma (LSS) is a methodology that combines lean principles and Six Sigma (Sakthivelmurugan et al., 2021). Lean principles eliminate waste and non-value-added activities from these processes (Xiong et al., 2019) and emphasize identifying and eliminating activities that do not contribute to creating customer value. They include continuous improvement, value stream mapping, standardized work, visual management, and just-in-time production (Valamede & Akkari, 2020). Six Sigma is a data-driven approach that reduces process variability (Clancy et al., 2023). It follows a structured approach to problem-solving, the most common of which is DMAIC (Define, Measure, Analyze, Improve, and Control). Six Sigma emphasizes using statistical tools and techniques to measure and analyze process performance (Madhani, 2020). By applying the LSS principles and tools, construction companies can increase process efficiency, reduce waste, enhance quality, and achieve better project outcomes. These improvements can lead to cost savings, increased customer satisfaction, and a competitive position in the construction industry. Construction projects frequently experience delays, increased costs, and client dissatisfaction. LSS can help identify bottlenecks, streamline workflows, and reduce cycle times, improving project scheduling and ensuring timely completion (Cesarotti et al., 2019). Moreover, poor-quality construction projects can result in rework, customer complaints, and increased costs. LSS focuses on improving quality by identifying and addressing the root causes of defects, implementing standardized processes, and continuously monitoring and improving quality performance.

Although lean construction approaches are relatively new, research has indicated that they can reduce costs by up to 25% compared with conventional project management strategies (Al-Aomar, 2012; Koskela, 1997). Ballard and Howell (2003) reported that implementing lean construction techniques has significantly benefited multiple countries.

Several LSS studies have been conducted on construction projects. The method applied in the LSS involves extensive data during the construction phase and cannot be implemented at an early stage of the project, which makes it more rigorous, more complex, and less dynamic. In the present study, two indicators – the sigma rating (SR) and value-added ratio – are employed in earned value management (EVM) to address this gap. This integration allows managers to measure project quality, performance, and flow management during project implementation. Dynamic systems employ two interconnected models for waste causes (WCs) and quality causes (QCs). Another contribution of this study is the simulation of different scenarios to predict a project's performance quality and flow at an early stage. These scenarios can be modeled by controlling the strength and duration of each WC and QC in the developed system dynamics (SD).

Integrating LSS, SD, and EVM provides construction managers with a comprehensive toolkit for data-driven decision-making. SD modeling allows the exploration of various scenarios and their long-term effects on project performance. EVM provides real-time insights into project progress and allows proactive decision-making. These approaches help managers make informed decisions to optimize resources, improve processes, and mitigate risks. In addition, the LSS metrics can be integrated into the EVM calculations. This integration provides a more accurate assessment of project performance, allowing construction managers to track the effects of the LSS initiatives on cost, schedule, and quality outcomes, which provides a holistic view of project performance, facilitating proactive interventions and continuous improvements. SD modeling allows the analysis of the long-term impact of LSS initiatives on construction projects. This model allows construction managers to simulate and evaluate the effects of process improvements, quality enhancements, and waste reduction strategies over time. The present study also helps understand how project parameter changes influence performance metrics, allowing proactive planning and decision-making. The combination of LSS, SD, and EVM fosters a culture of continuous improvement in construction management.

2. Literature review

Lean management and Six Sigma have several indices for measuring waste quality. None of these indices, such as EVM, was used as an indicator to control project progress. Managers cannot measure the project progress to reduce waste or improve quality. Additionally, the current measured time and cost indices, such as those used in the EVM technique, do not measure quality and waste. This section covers studies in the two areas mentioned to illustrate the research gap.

2.1. Studies on LSS methods

Many studies have focused on integrating lean principles, which aim to eliminate waste and improve process flow, with Six Sigma, emphasizing the reduction of process variations and defects (Al-Aomar, 2012; Hussain & Kumar Paharia, 2018; Jowwad et al., 2017; Oguz et al., 2012; Linde & Philippov, 2020; Yang & Deng, 2023). These studies explored the synergies between the two approaches and highlighted their benefits in improving process performance, customer satisfaction, and organizational effectiveness.

2.2. Studies on Six Sigma, Lean management, and EVM indices for construction projects

There are several Six Sigma indices, such as defects per million opportunities (DPMO), process capability (Cp), defects per unit (DPU), rolled throughput yield (RTY), and SR. The most commonly used index is the SR, which represents the number of standard deviations that can fit between the process mean and the nearest specification limit. This index has been developed and used in several fields. Yang and Deng (2023) used SR in graphical applications. Computing the sigma index involves iterating over all the edges of the graph and summing the squared degrees of the vertices connected by each edge. Ali et al. (2023) explored the sigma index of graphs. Concerning construction, Al-Aomar (2012) investigated the feasibility of using SRs. This index is based on the number of total units and defects units.

In lean management, several fundamental indices are used to track and assess the process performance and identify development opportunities. Widely used indicators in lean management include lead time, cycle time, defect rate, value-added ratio, and work-in-progress. The common index is the value-added ratio, which compares the value-added time (the time spent on activities that directly contribute to the product/service) to the total lead time. It helps identify non-value-added activities and opportunities for waste reduction. Setijono and Dahlgaard (2007) discussed the relationship between added value and the value created by customers to complement the performance measures in Six Sigma and Lean Production. The value-added ratio was used to examine the efficiency of allocating productive sources by studying micro-level data from China to empirically test its impact and mechanism in China (Zhang et al., 2024).

The EVM is a project management technique used to measure project performance and progress regarding cost and schedule. It utilizes several key indices to assess and forecast project performance. Koke and Moehler (2019) highlighted the possibility of using EVM in sustainability applications. According to a literature review, approximately 14 indices were derived from the EVM method using the equations presented in Table 1. Common indices were summarized by Proaño-Narváez et al. (2022) as the

Table 1. Indices derived from EVM

References	Cost Performance Index (CPI)	Schedule Performance Index (SPI)	Cost Variance (CV)	Schedule Variance (SV)	Estimate at Completion (EAC)	Variance at Completion (VAC))	Profitability index (PPI)	GHG* performance index (GPI)	Z-number-based EVM	Last planner system (LPS)	Customer Earned Value (CEV)	Quality Performance Index (QPI)	Cost risk index (CRI)	Scope change on the project plan
Proaño-Narváez et al. (2022)	×	×	×	×	×	×	–	–	–	–	–	–	–	–
Leon et al. (2018)	×	×	–	–	–	–	×	–	–	–	–	–	–	–
Pascual et al. (2021)	×	×	×	×	×	×	–	–	–	–	–	–	–	–
Vanhoucke and Vandevoorde (2007)	×	×	×	×	×	×	–	–	–	–	–	–	–	–
Abdi et al. (2018)	–	–	–	–	–	–	–	×	–	–	–	–	–	–
Koke and Moehler (2019)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Hendiani et al. (2020)	–	–	–	–	–	–	–	–	×	–	–	–	–	
Kim et al. (2015)	–	–	–	–	–	–	–	–	–	×	–	–	–	–
Kim and Ballard (2002)	–	–	–	–	–	–	–	–	–	–	×	–	–	–
Kim et al. (2016)	–	–	–	–	–	–	–	–	–	–	×	–	–	–
Gallego and Gutiérrez (2017)	–	–	–	–	–	–	–	–	–	–	–	×	×	–
Tariq et al. (2020)	–	–	–	–	–	–		–	–	–	–	–	–	×

Cost Performance Index (CPI), Schedule Performance Index (SPI), Cost Variance (CV), Schedule Variance (SV), Estimate at Completion (EAC), and Variance at Completion (VAC). Table 1 presents the indices derived through the EVM.

2.3. Knowledge gap

According to the literature, no studies have integrated EVM's SR and value-added ratio to monitor and improve project performance throughout construction continuously. In addition to the limitations of the various methods used in LSS, these methods require more flexibility to deal with the dynamic changes during construction. In addition, they cannot be applied early in the process, and future performance cannot be predicted. Moreover, some surgical methods cannot be standardized. Researchers have applied these techniques to construction projects as case studies. However, no study has provided a systematic method for applying LSS in construction projects while providing quantitative indicators that reflect project quality performance and construction project implementation management during the construction period.

This study used SD and EVM to apply LSS to construction projects using the significant WCs' and QCs' interdependencies for housing infrastructure projects. The significant WCs and QCs were determined by surveying and measuring the degree of influence of 63 WCs and 33 QCs. Different scenarios were generated depending on the statuses of the QCs and WCs. Quality performance and lean management were measured using SRs and lean indices and monitored throughout the project duration for each scenario. These indices can be computed using EVM principles, representing the significance of this study.

3. Methodology

The methodology consisted of four steps: data collection, ranking of WCs and QCs, creation of causal loop diagrams, and integration of CLDWCs (causal loop diagram of waste causes) and CLDQCs (causal loop diagram of quality causes) into the SD, as shown in Figure 1. The primary purpose of the data collection was to identify the WCs and QCs in the literature and current housing infrastructure construction projects. The ranks of the WCs and QCs were determined by administering a questionnaire to measure the degrees of influence of the WCs and QCs and applying the RII method. DEMATEL was implemented on the top 10 WCs and QCs to create causal loops. These CLDs were integrated into the SFD (stock flow diagram) to study the LSS principle using SD.

3.1. Data collection

Data were obtained on the importance and degree of WCs and QCs that may influence housing infrastructure projects, and the top 10 were used to establish the CLDWCs and CLDQCs using DEMATEL techniques. A preliminary list of frequently reported reasons for WCs and QCs in the KSA and many other nations was compiled through extensive literature research (Alarcón, 1997; Issa, 2013; Jowwad et al., 2017). Three semi-structured interviews were conducted to facilitate the provision and reception of data and to permit conversational and two-way contact at this stage (Mosaad et al., 2018). The main objective of these interviews was to specify WCs and QCs by filtering the preliminary list and counting, combining, or reporting causes to explain the current situation in the KSA construction industry.

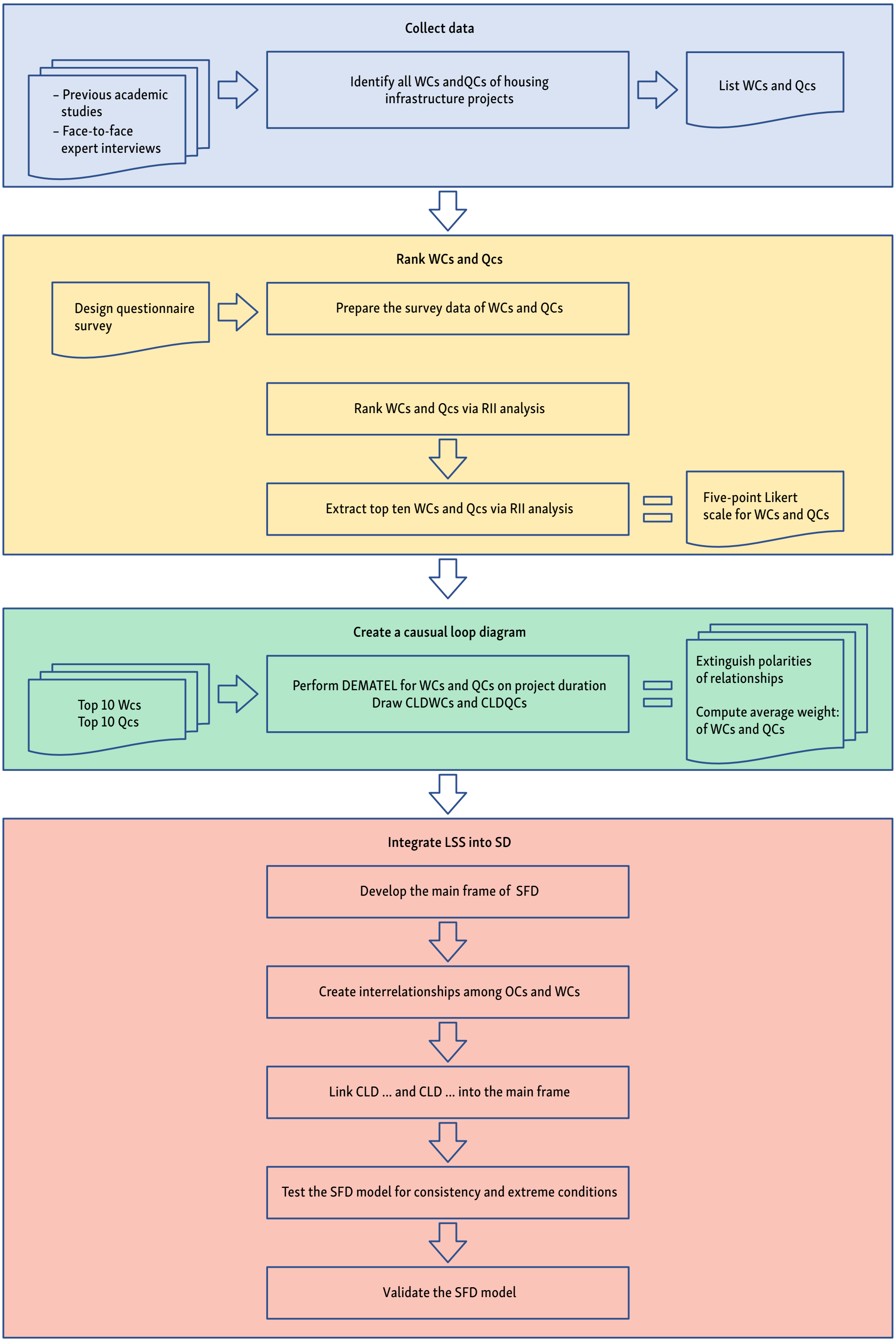

Figure 1. Methodology of this study

Consequently, nine experts were given the three lengthy dissections. The experts comprised five contractor project managers and four consulting office project directors of megaprojects in the Kingdom of Saudi Arabia. Nine of the experts possessed over 25 years of experience. The 63 WCs and 33 QCs are shown in Tables A1 and A2 in Appendix, respectively.

3.2. Ranking of WCs and QCs

3.2.1. Survey

A questionnaire was created based on primary and secondary data acquired via in-depth literature reviews and semi-structured interviews with industry professionals involved in the infrastructure-building housing projects in the Kingdom of Saudi Arabia. A pilot survey assessed whether the questionnaires were valid and sufficient. There were two sections to it. The first part asked for the experts' demographic data. The various factors influencing building quality were discussed in the second section. The factors were divided into groups based on their ability to group the causes under the accountable categories. The experts were asked to indicate the importance level of each factor that affects quality, according to their experience. They were given closed-ended questions and options for scoring on a five-point Likert scale.

The survey was sent to 300 Saudi construction industry experts with adequate experience supervising and executing construction projects. Through e-mail, personal interviews, and direct observation, 47 participants responded to the questionnaire. In this study, more than 57% of the survey professionals had >15 years of experience managing or implementing building projects. The degree of reliability of the data provided by the respondents is indicated by their credentials, which include an M.Sc., Ph.D., consulting certificate, or PMP certificate, as well as their experience working on construction projects. Their opinions reflect the current state of the industry.

3.2.2. Preparation of survey data of WCs and QCs

The responses to the second part of the questionnaire were recorded as scores of 1–5 in MS Excel. When a respondent selected two options for a particular question, the responses were regarded as missing data and were handled using SPSS. According to the participants' responses, there were two types of anomalous data: 1) the participant selected multiple points on the Likert scale; 2) the question was not answered (missing data). The mean of nearby points method was used in this study. To handle missing data, the data were exported to an MS Excel file for further processing after treatment in SPSS.

3.2.3. Ranking WCs and QCs via RII analysis

The importance level of each cause was identified using the Relative Importance Index (RII) (Akadiri, 2011; Akadiri et al., 2013).

3.2.4. Extracting top 10 WCs and QCs via RII analysis

According to RII computations, 63 WCs and 35 QCs factors were ranked. The top 10 WCs and QCs are presented in Tables 2 and 3, respectively, with the corresponding RII values. The RII values of the WCs range from 0.796 to 0.826. In contrast, the RII values of the top ten QCs range from 0.774 to 0.839.

3.3. Creation of causal loop diagram

3.3.1. Perform DEMATEL for WCs and QCs on project duration

This section establishes a causal model for significant causes of waste and quality. It utilizes the DEMATEL approach to define the influence of polarities among the ten significant waste factors and determine their weights. DEMATEL depends on participants' opinions rather than the sample size.

Table 2. Top 10 significant WCs

No	Symbol	Description	RII
1	WC1	Reducing labor productivity and increasing unskilled workers	0.826
2	WC2	Late in site delivering materials	0.813
3	WC3	Slow response and decision from the Client	0.809
4	WC4	Delaying design documents approval	0.804
5	WC5	Lack of contractor experience in cooperating with his/her laborers	0.804
6	WC6	Increase of reworking project items due to poor execution.	0.804
7	WC7	Lack of supervision and material control that causes wastage	0.804
8	WC8	Poor management workers, such as inadequate motivation or improper accommodations	0.800
9	WC9	Alterations in the project scope	0.800
10	WC10	Shortage of skilled labor	0.796

Table 3. Top 10 significant QCs

No	Symbol	Description	RII
1	QC1	Skill experience of contractor site team	0.839
2	QC2	Skill and experience of supervision staff	0.830
3	QC3	Deficiency of planning and management by the contractor	0.804
4	QC4	Poor quality of contractor's work	0.796
5	QC5	Increasing morale and attitude affect the quality of the project	0.783
6	QC6	Lack of communication between supervision staff and contractor's staff	0.783
7	QC7	Lack of communication and coordination within the contractor site team	0.779
8	QC8	Increase of errors and omissions in design documents	0.779
9	QC9	Having design documents shortage and inconsistency	0.779
10	QC10	Lack of communication between supervisors and laborers affects construction quality	0.774

A sample size between 10 and 30 has been employed in most studies, according to a literature review on DEMATEL-defined sample sizes (Asadi et al., 2022; Bavafa et al., 2018). Thus, a sample size of 15 specialists was adequate for gathering information for the study's analysis. The experts were interviewed face-to-face as part of the poll. This strategy emphasizes the contractor's responsibility more than the other parties. The participants held jobs in the Saudi government and various other commercial sectors.

The experts were contractors and consultants with 10–15 years of experience in the construction sector. Experts were consulted on how the interactions between the waste factors affected one component. The results of the DEMATEL were total relation matrix for WCs and QCs as shown in Tables 4 and 5, respectively. Moreover, the threshold values (αWCs = 0.492, αQCs = 0.680) for TWCs and TQCs were determined to evaluate the relationships among the WCs and QCs, respectively. For more details of DEMATEL computations, the reader should refer to Al-Gahtani et al. (2024).

3.3.2. Draw CLDWCs and CLDQCs

The CLDWCs and CLDQCs were drawn according to Tables 5 and 4, and the value of α, as shown in Figures 2 and 3, respectively. The most significant causes of waste were WC9 and WC10, which influenced the remaining waste. On the other hand, the QC10 represents the quality caused by the top 10 QCs except QC5.

3.4. Integration of LSS into SD

3.4.1. Develop main frame of SFD

The central frame concept developed in Al-Gahtani et al. (2024) was based on the assumption that two errors occur during project implementation. The first error type is errors that lead to changing orders, e.g., changing the owner's vision of the project, the site condition being different from what is planned, and other errors. The second type of error is rework error. The main framework consists of five stocks and six flows. The first stock is the percentage of tasks that must be performed. The second stock is the percentage of tasks performed without quality checks. The third stock is the percentage of tasks that require document modification. The fourth stock is the percentage of tasks performed with implementation defects and required rework. The fifth stock is the percentage of completed tasks.

The first stock is connected to the second stock by a progress rate flow (F1), represented by the project's schedule plan, as shown in Figure 4. The first error type can be modeled in the main frame using the first stock, third stock, flow 2 (detected rate of task required change order; F2), and flow 3 (repair rate of change order task; F3), as shown on the left side of the main frame. Similarly, the second type of error can be represented by the second stock (% of tasks performed without examination), fourth stock (% of tasks requiring rework), flow 4 (detected rate of work error; F4), and flow 5 (repair rate of

Table 4. Values of the total relation matrix *T* of WCs

WCs	WC1	WC2	WC3	WC4	WC5	WC6	WC7	WC8	WC9	WC10
WC1	0.32	0.37	0.37	0.37	0.39	0.44	0.40	0.41	0.43	0.45
WC2	0.40	0.33	0.38	0.40	0.40	0.41	0.41	0.41	0.43	0.46
WC3	0.44	0.44	0.35	0.44	0.45	0.48	0.46	0.47	0.48	0.50
WC4	0.48	0.47	0.47	0.39	0.48	**0.52**	**0.50**	**0.50**	**0.52**	**0.53**
WC5	0.46	0.46	0.44	0.48	0.40	**0.52**	**0.50**	**0.51**	**0.53**	**0.53**
WC6	**0.49**	0.48	0.47	0.48	0.50	0.45	**0.50**	**0.51**	**0.53**	**0.55**
WC7	**0.52**	**0.51**	**0.50**	**0.51**	**0.53**	**0.58**	0.45	**0.55**	**0.57**	**0.58**
WC8	**0.55**	**0.53**	**0.52**	**0.55**	**0.57**	**0.61**	**0.57**	0.48	**0.60**	**0.61**
WC9	**0.56**	**0.58**	**0.56**	**0.56**	**0.59**	**0.64**	**0.60**	**0.60**	0.52	**0.62**
WC10	**0.54**	**0.53**	**0.50**	**0.52**	**0.53**	**0.59**	**0.56**	**0.56**	**0.57**	0.49

Table 5. Values of the total relation matrix *T* of QCs

QCs	QC1	QC2	QC3	QC4	QC5	QC6	QC7	QC8	QC9	QC10
QC1	0.54	0.62	0.61	0.66	0.62	0.65	0.66	**0.71**	**0.76**	**0.75**
QC2	0.61	0.54	0.60	0.66	0.62	0.64	0.65	**0.70**	**0.77**	**0.75**
QC3	0.60	0.60	0.51	0.64	0.61	0.63	0.65	0.68	**0.74**	**0.73**
QC4	0.62	0.63	0.60	0.59	0.65	0.66	0.67	0.70	**0.75**	**0.75**
QC5	0.60	0.58	0.56	0.63	0.52	0.61	0.63	0.66	**0.71**	**0.71**
QC6	0.62	0.61	0.61	0.67	0.63	0.57	0.67	0.71	**0.76**	**0.75**
QC7	**0.68**	0.67	0.65	**0.72**	0.68	**0.71**	0.63	**0.75**	**0.82**	**0.80**
QC8	0.66	0.67	0.65	**0.72**	0.68	**0.70**	**0.72**	0.66	**0.82**	**0.79**
QC9	**0.71**	**0.71**	**0.70**	**0.77**	**0.73**	**0.74**	**0.76**	**0.80**	0.75	**0.84**
QC10	**0.71**	**0.70**	**0.69**	**0.75**	**0.72**	**0.73**	**0.75**	**0.78**	**0.83**	0.73

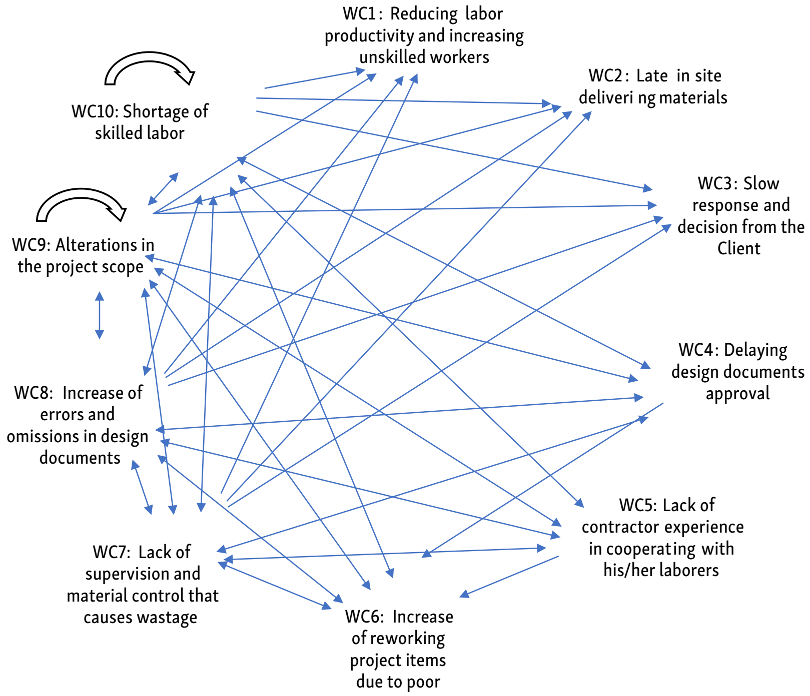

Figure 2. Casual loop diagram of WCs

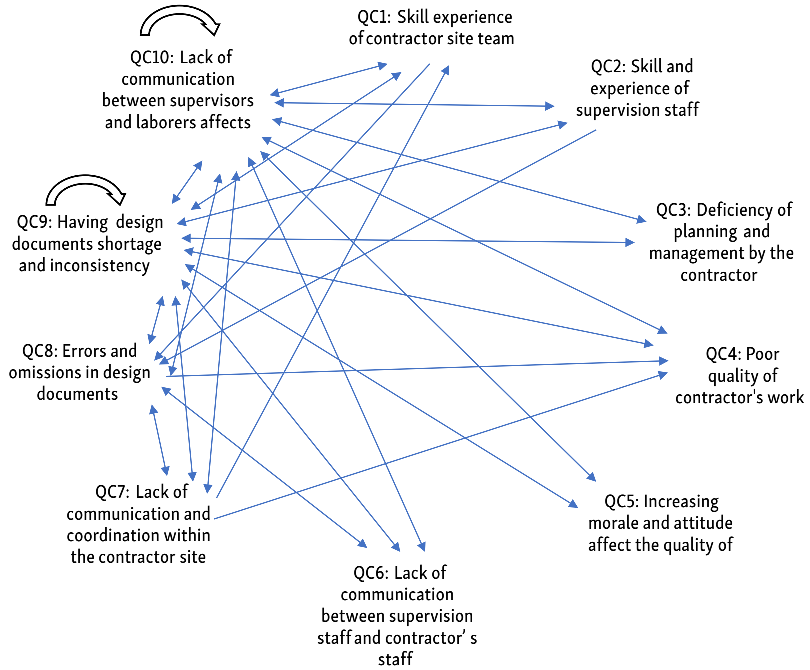

Figure 3. Casual loop diagram of QCs

tasks for rework; F5), as shown on the right-hand side of the main frame in Figure 4. The first stock (tasks waiting to be performed), F1, F2, and F3 control the second stock (PerformedTasks WithoutQualityCheck). Therefore, two links were constructed: F2 to F1 and F3 to F1. The second set of PerformedTasksWithoutQualityCheck, F4, F5, and F7 controls the stock of CompletedTask. Therefore, three links were performed from F4 to F5, and the stock of Performed-TasksWithoutQualityCheck to F7, as shown in Figure 4.

3.4.2. Create interrelationships among QCs and WCs

First, the top 10 WCs or QCs were modeled by ten dynamic convectors in the SFD of the AnyLogic software (Anylogic, 2023). The developed CLD was utilized to analyze the polarities between the WCs and QCs. Techniques illustrating (Al-Gahtani et al., 2024) the integration of CLD into SFD were used in this study. Self-relations and two-way relationships cannot be represented in SFD. The two-way relationship was converted into a relationship by omitting

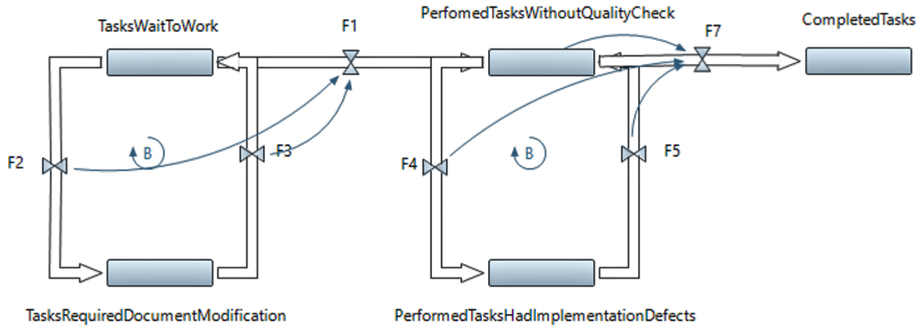

Figure 4. Main frame of the SFD

one of the relations that had a smaller α-value. For example, two relationships existed between WC9 and WC10; the α-values of (WC9→WC10) and (WC10→WC9) were 0.62 and 0.57, respectively, as shown in Table 5. Therefore, WC9→WC10 was considered in the SFD because it had a higher α-value than WC10→WC9. The interrelationships between the WCs and QCs in the SFD were drawn according to Table 4 and 5, respectively.

3.4.3. Link CLD_{WCs} and CLD_{QCs} into the main frame

This section discusses the use of WCs and QCs in the main framework. Al-Aomar (2012) and Linde and Philippov (2020) stated that quality is related to variability and errors in any process, whereas waste influences the speed of the plan, schedule, and progress. In this study, the errors were F2 (defective rate of change order) and F4 (defective rate of reworking tasks). The progress and schedule plan flows were F1 (planned schedule), F3 (repair rate of change order), and F5 (repair rate of rework tasks). Therefore, the top 10 WCs influenced F1, F3, and F5. In addition, the top 10 QCs impacted F2 and F4. However, the following issues were raised: What WCs affect F1, F3, and F5, and how much do they affect them? The same issues were raised regarding the QCs for F2 and F4.

Consequently, structured interviews with ten experts in housing infrastructure projects were conducted to overcome the above issues. The experts assigned percentages of WCs and QCs to the flows, as shown in Tables 6 and 7. The WCs and QCs were connected to the main frame, as indicated by the red links in Figure 5. The connections of the WCs and QCs to the main frame are represented by red and green links, respectively, to simplify the developed SFD.

Table 6. Effects of WCs on F1, F3, and F5

WCs	F1	F3	F5	$\sum F_i$	%WC_i on F_j $\left(\overline{F_j} = F_j / \sum F_j\right)$		
					F1	F3	F5
WC1	0.25	0.3	0.15	0.7	0.357	0.429	0.214
WC2	0.1	–	0.05	0.15	0.667	–	0.333
WC3	0.05	0.05	0.05	0.15	0.333	0.333	0.333
WC4	0.05	0.05	0.05	0.15	0.333	0.333	0.333
WC5	0.13	0.1	0.1	0.33	0.394	0.303	0.303
WC6	0.12	0.1	0.2	0.42	0.286	0.238	0.476
WC7	0.1	0.1	0.1	0.3	0.333	0.333	0.333
WC8	0.05	0.05	0.05	0.15	0.333	0.333	0.333
WC9	0.05	0.1	0.1	0.25	0.200	0.400	0.400
WC10	0.1	0.15	0.15	0.4	0.250	0.375	0.375
∑	1	1	1				

Table 7. Impact of QCs on F2 and F4

QCs	F2	F4	$\sum F_i$	%QC_i on F_j $\left(\overline{F_j} = F_j / \sum F_j\right)$	
				F2	F4
QC1	0.05	0.3	0.35	0.143	0.857
QC2	0.15	0.1	0.25	0.600	0.400
QC3	–	–	–	–	–
QC4	–	–	–	–	–
QC5	0.2	0.2	0.4	0.500	0.500
QC6	0.05	0.2	0.25	0.200	0.800
QC7	0.2	–	0.2	1.000	–
QC8	0.2	–	0.2	1.000	–
QC9	0.1	0.2	0.3	0.333	0.667
QC10	0.05	–	0.05	1.000	–
∑	1	1	2		

3.4.4. Test SFD model for consistency and extreme conditions

The ability of the SFD model to obtain proper and logical findings was evaluated by conducting consistency and extreme-condition tests. The developed SFD model conformed to a uniform set of units. Thus, the units of the five stocks are consistent regarding the percentage of tasks. Accordingly, the unit of the six flows (F1, F2, F3, F4, F5, and F6) is the rate of change of the percentage of tasks with time. In contrast, the objective of the extreme-condition test is to compare the structure of the existing system with that of the SFD. Consequently, the test determines whether the actual system behavior under the same circumstances matches the model structure under extreme circumstances. Hence, in the absence of WCs and QCs, CompletedTasks follow an S-curve that starts from zero at the beginning and reaches 100% at the end. In other words, the anticipated progress curve resembles the planned progress curve (PPC) when the values of WCs and QCs equal zero.

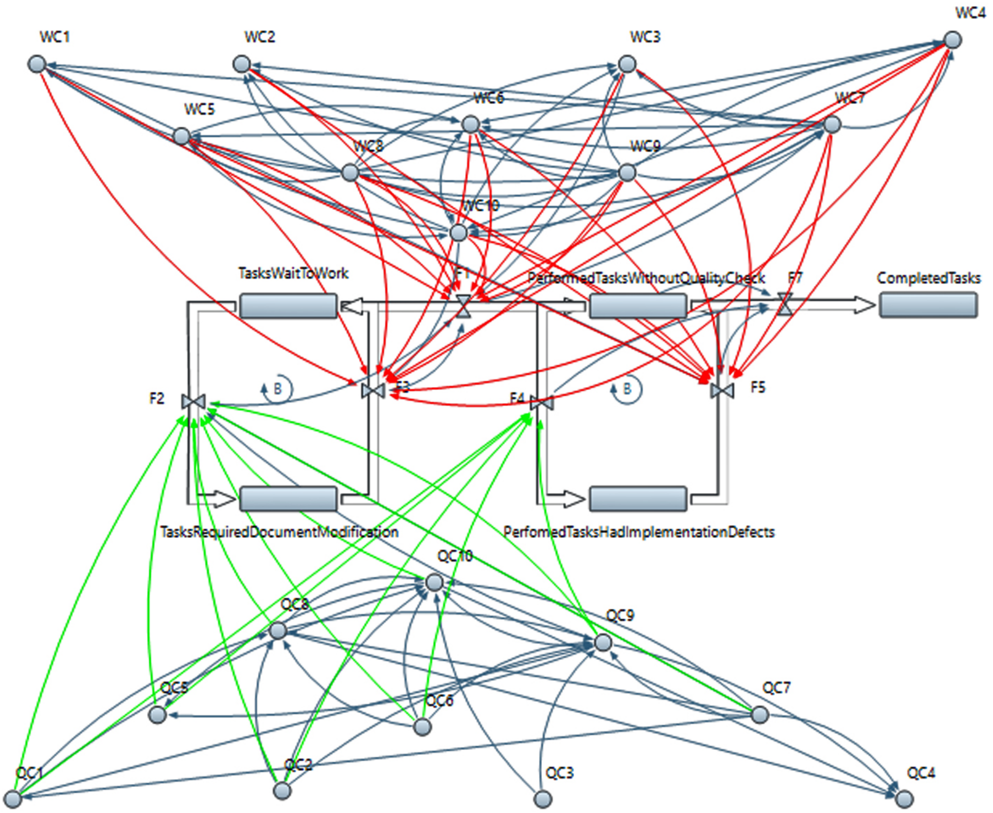

Figure 5. Developed SFD

3.5. Measurement of SR and speed indices

The purpose of using the LSS principles is to improve organizational processes' quality, efficiency, and effectiveness. LSS combines lean management and Six Sigma philosophies and methodologies to drive operational excellence and continuous improvement. Consequently, two metrics were utilized in this study: the first was related to lean management, and the second was the SR – a statistical index related to Six Sigma. The two indices were computed for several planned project durations to evaluate and improve performance.

3.5.1. Lean index computation

No indices will be applied to measure lean management – particularly in construction projects.

This study developed a metric based on the derivative at three prescribed points on two progress curves. The first curve represents the progress curve corresponding to the plane schedule and is called the plane curve, whereas the second curve is the progress curve generated by eliminating WC. The curves are fitted according to the S-curve function using Eqn (1):

$$P = A \times \left(1 - exp\left(-B \times Time^{C}\right)\right), \quad (1)$$

where P is the progress value, and time is a portion of the planned duration, which changes from 0.00 to 1.00. A, B, and C are constants. The two fitted functions are derived concerning the projection time (t). The general derivative-fitted function can be computed using Eqn (2):

$$\frac{\partial P}{\partial Time} = A \times B \times C \times Time^{C-1} \times \left(-B \times Time^{C}\right). \quad (2)$$

Subsequently, the $\frac{\partial P}{\partial Time}$ values at 0.25, 0.50, and 0.75 can be determined for each curve. $\Delta Time_{Plane}$ and $\Delta Time_{Forecast}$ at 0.25, 0.50, and 0.75 can be computed for two curves (plan progress curve and forecast progress curve, as shown in Figure 6) according to the values of $\frac{\partial P}{\partial Time}$ for the plane and forecast curve and Eqns (3) and (4) with the change of progress $\left(\Delta P_{Plane}\right)$ set as 1%.

$$\left(\frac{\partial P}{\partial Time}\right)_{Plane} = \frac{\Delta P_{Plane}}{\Delta Time_{Plane}}; \quad (3)$$

$$\left(\frac{\partial P}{\partial Time}\right)_{Forecast} = \frac{\Delta P_{Forecast}}{\Delta Time_{Frecast}}. \quad (4)$$

The value-added ratio (*VAR*) is the ratio of the summation of the change times of the three specified points on the plane to the forecast progress curve given by Eqns (5)–(7):

$$\sum_{i=1}^{n} \Delta Time_{Plane-i} = \Delta Time_{Plane-1} + \Delta Time_{Plane-2} + ... + \Delta Time_{Plane-n}; \quad (5)$$

$$\sum_{i=1}^{n} \Delta Time_{Forecast-i} = \Delta Time_{Forecast-1} + \Delta Time_{Forecast-2} + ... + \Delta Time_{Forecast-n}; \quad (6)$$

$$VAR = \frac{\sum_{i=1}^{n} \Delta Time_{Forecast-i}}{\sum_{i=1}^{n} \Delta Time_{Plane-i}}. \quad (7)$$

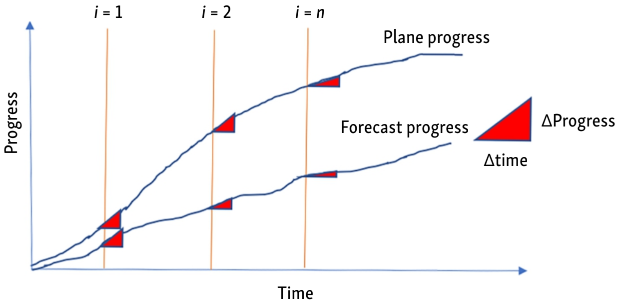

Figure 6. Sketch of VAR computation

3.5.2. SR computation

The SR, sigma level or Six Sigma level is a statistical measure used to quantify a process' capability and quality performance. It is generally associated with the Six Sigma methodology, which aims to reduce the number of defects and increase process efficiency. The SR counts the defects or errors per million opportunities (DPMO). It indicates a process' performance and provides a standardized way to compare and evaluate process performance across different industries and organizations. The SR was derived from the operational capability index. It compares the process variation with the specified tolerance limits and indicates the potential for defects. A lower defect rate corresponds to better process performance.

The SR can be computed according to EVM. The plan and forecast progress curves were obtained, as shown in Figure 7. The SR at the *i*th planned time duration (SR_i) is based on the percentage of performed tasks (TT_i), which is the planned progress value at the planned project time (Time), and the percentage of defect tasks (DT_i). DT_i is the difference in progress values between the plane and forecast curves at the *i*th timestep, as shown in Figure 7. The overall yield (Y) can be computed using Eqn (8):

$$Y = 1 - \frac{DT_i}{TT_i}. \quad (8)$$

The Z-score corresponding to the total yield value (*Y*) can then be estimated, and 1.5 is added to account for the performance shift to convert the result into an SR. Excel was used to calculate the Z-scores. One way to represent the SR formula is using Eqn (9) (Al-Aomar, 2012).

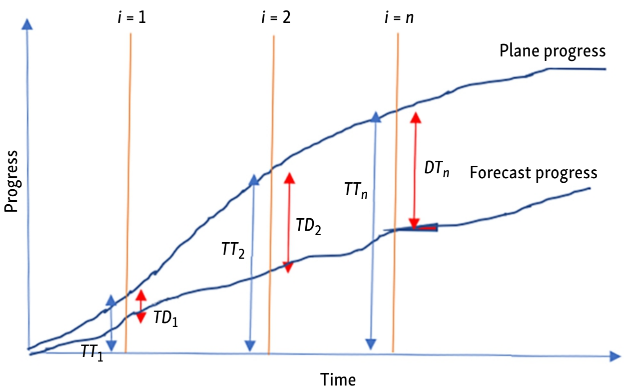

Figure 7. Sketch of SR computation

$$SR = NORMSINV\left(Y\right) + 1.5. \quad (9)$$

The computed SR value is compared with the SR's company standard or benchmark values to determine whether a DMAIC Six Sigma improvement study is needed (Al-Aomar, 2012).

4. Results and discussion

This section presents the results in three subsections: the influence of eliminating WCs on project duration (lean management), the influence of QCs on project duration, and the influence of a combination of WCs and QCs on project duration (LSS management).

4.1. Influence of elimination of WCs on project time

The VAR ratios for different scenarios of WC elimination were studied. The VAR indicates the reduction ratio of the project time due to eliminating WCi from the construction project activities. Section 4.5 calculates the VAR using three discrete times: 0.2, 0.50, and 0.75 of project time. The VAR of the WCs is 0.715, as shown in Figure 8. In other words, eliminating all the WCs reduced the project time to 0.715 at 0.75 of the project time. As shown in Figure 8, WC8, WC9, and WC10 had VAR values of < 0.9. This result was attributed to WC8, WC9, and WC10 interaction. In contrast, the VAR values of WC1, WC3, and WC6 were > 0.95, indicating that they have little influence on reducing project time owing to their limited relationships with other WCs, as shown in Figure 2.

4.2. Six Sigma performance of QCs

Six Sigma performance can be evaluated using the SR metric. The SR can be used to reduce defects and errors during a process. The quality control and assurance of construction projects can be enhanced by providing higher SRs. This enhancement can lead to improved construction practices, better artistry, and a higher standard for finished housing infrastructure. The SR focuses on process improvement and optimization. By analyzing the causes of defects and errors, the project team can identify areas for process enhancement, implement corrective measures, and continually refine construction practices. This analysis can increase efficiency, reduce variability, and improve overall project performance. Figure 9 shows the SR for 11 scenarios at 0.25, 0.50, and 0.75 of the project's planned duration. The first scenario represents the effect of all the quality control centers, while the other scenarios represent the effects of every QC (QC1–QC10). In general, the SR increased slightly with time. This result was attributed to the increasing percentage of total tasks (TT) compared with the percentage of defect tasks (DT). The results presented in Figure 9 depend on the assumption that the factor is created or generated at the beginning of the project and continues until the end of the project (worst-case scenario).

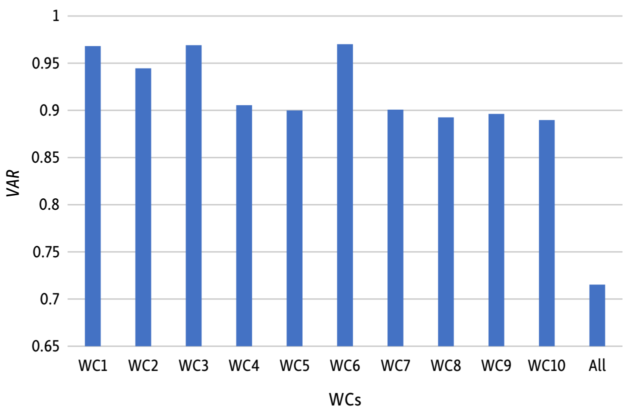

Figure 8. *VAR* values for different scenarios of WC elimination

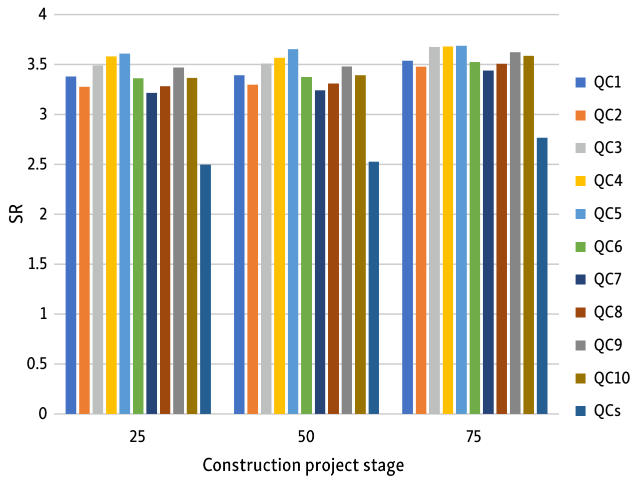

Figure 9. SR values at several project times

In addition, the SR values for each QC in several projects exceeded 3.00. Therefore, the DMAIC techniques are not required. However, the SRs for all QCs were 2.48, 2.54, and 2.75 for 0.25, 0.50, and 0.75 of the project's planned duration, which were lower than 3.00. DMAIC techniques are required to improve the project quality. A value is probably lower than 3 for any two or more QCs. Hence, the SD model provides value for monitoring SR in different scenarios. The advantage of the SD model is that it allows different levels of quality control during the project period, facilitating monitoring and improvement. This paper presents the identification, measurement, and analysis of QCs together and each QC separately due to space limitations. As shown in Figure 9, the worst QC was QC7 (Lack of communication and coordination within the contractor site team). Timely detection and resolution of quality concerns may be impeded by inadequate communication and coordination.

In the absence of efficient channels for communication, issues can be ignored or remain unreported, delaying the resolution process. This elimination may lead to additional effort, higher expenses, and schedule delays, affecting a project's quality. Abas et al. (2022) identified QC7 as a critical risk to project success. The second and third orders of QCs are QC8 (Increase of errors and omissions in design documents) and QC2 (Skill and experience of supervision staff), respectively. Errors in design documents can lead to construction deficiencies where the actual construction aligns differently from the intended design. This finding can result in structural problems, a lack of artistry, and compromised functionality in the built environment. Such defects can negatively influence overall project quality (Herrera et al., 2020). In addition, low skill and lack of experience affect project quality (Zaray et al., 2022). Skilled supervision staff members are experienced in executing adequate quality control and assurance measures throughout the project lifecycle. The experienced staff can help develop and enforce quality management plans, conduct regular inspections, and perform quality checks to verify compliance with design documents and quality standards. Their attention to detail and ability to identify deviations or deficiencies early can prevent the escalation of quality-related problems.

4.3. LSS performance

Figure 10 shows the progress curves for the three conditions. The first condition is the planned schedule progress (blue curve). The second condition represents eliminating the WCs (orange curve). The third condition is the project's progress, which has all the QCs (gray pointed curve). The WCs reduced the project time, and the progress was 100% at a project time of 0.68 of the planned schedule, as shown in Figure 10. Regarding the progress curve of the QCs, the progress at the end of the planned duration of the project was 89.19%, as shown in Figure 10.

The previous results dealt with the sensitivity analysis of the WCs and QCs separately at different stages of the project time. In this section, QCs are analyzed with the elimination of all WCs to examine the impact of waste management on the overall quality of the project. To achieve this analysis, the WCs were omitted from all scenario simulations. Thus, ten simulations were performed for each of the top 10 QCs. The SR was measured as 0.25, 0.50, and 0.75 of the project time for each simulation. Two curves were used for the SR computation. The first curve was a forecast

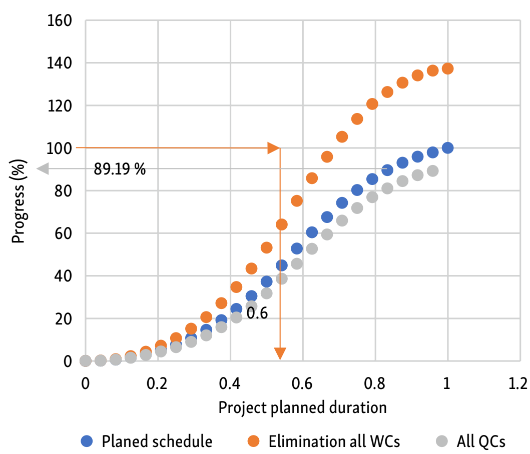

Figure 10. Progress curves of the different conditions

progress curve that omitted all the WCs, and the weights of all the QCs were set as zero. The second curve was a forecast progress curve obtained by eliminating the WCs and activating only one QC (QC1, QC2, etc.). The SR results for each QC at the three stages of the project were compared with the corresponding scenarios without the elimination of WCs, as mentioned in Section 5.2.

Figure 11 shows the SR values of the top 10 QCs at 0.25 of the project time for two situations: the elimination of WCs (blue bars in Figure 11) and the absence of elimination of WCs (brown bars in Figure 11). There was no difference in SR between the two situations. The identical values of SR are due to the convergence of the values of TT and DT in both situations because of the project's slow progress in its early stages. However, there is a slight difference in the SR values between the two situations at a project time of 0.50, which is larger than that for the second situation (without eliminating the WCs), as shown in Figure 12. The largest difference in the SR was observed at QC5. However, the difference in SR was minimal at QC8, whereas the difference was close to a constant value for the remaining QCs, as shown in Figure 12. The differences in SR were larger at 0.75 of the project time, as shown in Figure 13.

Similarly, at 0.50 of the project time, the maximum and minimum SR differences were recorded at QC5 and QC8, respectively, because QC8 had a larger weight value with many interactions with other QCs than QC5, which had a smaller weight value (0.093) with few interactions (two interactions), as shown in Figure 3. Therefore, improving project quality performance is more difficult for QC8 than QC5. Meanwhile, the *SR* difference at 0.75 of the project time has more variance than that at 0.50 of the project time, as shown in Figures 13 and 14. These variances are attributed to TT and DT increasing the project time, owing to the increasing function of the S-curve. According to the above information, eliminating WCs had little impact on the project at the early stage. These effects increased as the project progressed. A previous study by Al-Aomar (2012) confirmed that improving lean construction performance leads to improved project quality performance, regardless of the project time. It also removes waste or non-value-added tasks, enhancing production, reducing inventory, and improving product quality (Rajkumar & Biswas, 2016).

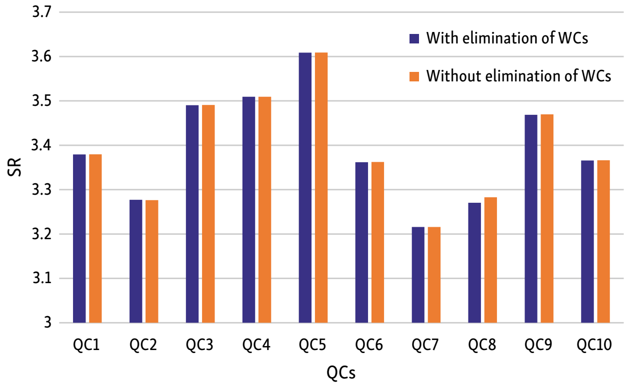

Figure 11. SR values of the 10 QCs with and without elimination of WCs at 0.25 of the project time

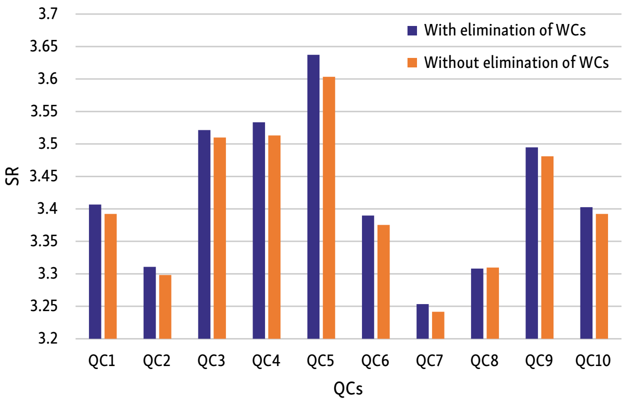

Figure 12. SR values of the 10 QCs with and without elimination of WCs at 0.50 of the planned time

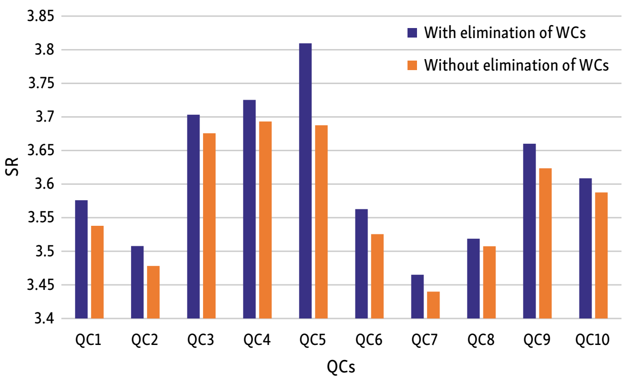

Figure 13. SR values of the 10 QCs with and without elimination of WCs at 0.75 of the planned time

5. Validation

The proposed sustainable development model was validated by comparing its output with the actual progress of four case studies from three project periods. Information on the four case studies, i.e., the total project land area and project time, is presented in Table 8.

The actual progress percentages of the four case studies at 0.25, 0.50, and 0.75 of the project time are shown in Figure 14. Planned progress for the SD model without eliminating WCs and without considering QCs is represented as planned progress in Figure 14. This curve is referred to as the PPC. The actual progress of the SD model represents the scenario that includes all QCs and is represent-

Table 8. General information of the four case studies

Classification	First case study	Second case study	Third case study	Fourth case study
Total project land area (m^2)	4,634,434	4,740,286	661,985	5,313,495
Project time (d)	450	540	364	450

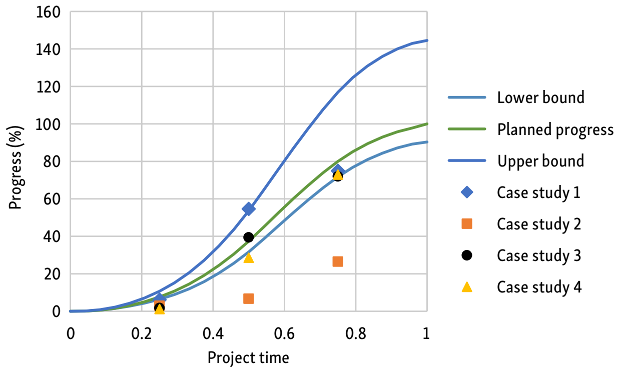

Figure 14. Progress values of the four case studies and the three-progress curve developed SD model

ed by the lower-bound progress curve. The progress curve generated by the developed SD model with the elimination of the WCs is represented by the upper-bound progress curve. In case study 1, the progress at 0.25 of the project time converged to the lower bound, far from the average and upper bound values. This finding is because the case study faced financial difficulties that impacted its progress.

In contrast, the progress at 0.50 of the project time was 54.6% higher than the corresponding lower and average values. However, the value converged to the upper bound with a difference of 3.4%. According to the project report, the contractor conducted several activities from 0.25 to 0.5 of the project time to increase productivity. Regarding case study 2, the progress values at 0.25, 0.50, and 0.75 of the project time were lower than the lower-bound progress curve, and the difference increased with increasing project time, as shown in Figure 14. The values of these differences at 0.25, 0.5, and 0.75 of the project time were 3.42%, 25.01%, and 45.32%, respectively. The project report revealed that the project experienced several halts and design changes. Therefore, the developed SD model cannot be applied to a task with several halts because its progress may not follow the S-curve. For case studies 3 and 4, the actual progress values at 0.50 and 0.75 of the project time converged to the planned and lower-bound progress curves. The progress values of the two case studies at 0.25 of the project time were slightly lower than the lower-bound progress curve, with a difference of < 5%.

According to the comparison results of the three case studies with the developed SD model, assumptions for applying the developed model are as follows: 1) The project has no halts during the construction stages, i.e., the progress follows the S-curve. Al-Gahtani et al. (2024) explained how the actual progress curve followed the S-curve by setting the average deviation between the fitted and actual points within the original project time of less than 10%.

6. Conclusions

Project performance is negatively impacted by wastes (non-value-added activities) and poor quality, which can lead to budget overruns and schedule delays. Lately, several studies highlight how LSS can boost quality, remove waste, increase process efficiency, and produce superior project results. Nevertheless, there are no general methods for applying LSS in building projects. The article combines SD, EVM, and LSS to provide a complete toolbox for data-driven decision-making in construction management. The methodology of the paper consists of several steps: collecting all WCs and QCs from the literature; measuring the impact degree of the WCs and QCs by designing and conducting a questionnaire survey; analyzing data and distinguishing the top ten WCs and top ten QCs using RII method; establishing causal loop diagram of the top ten WCs and QCs using DEMATEL method with 27 KSA building specialists; integrating CLDWC and CLDQC into SD to generate progress curves for different scenarios; computing the SR and LI metrices based on the generated curves and integrating the two metrices into EVM. The main findings revealed that eliminating all WCs reduces the project time to 0.7. The QCs decreased the progress at the end of the project to 89.1%. The elimination of WCs leads to increased SR with increasing time. The elimination of WCs has little impact on increasing the quality of project performance at an early stage of the project. These impacts increase with the increased progress of a project. The developed SD is offered as a way to support a continuous improvement culture in construction management and maximize resources, enhance procedures.

Author contributions

Conceptualization, Aljarallah, Al-Gahtani, Alsanabani, and Alsugair and; Data curation, Aljarallah; Formal analysis; Alsanabani, Aljarallah; Funding acquisition, Alsugair, and Aljarallah, Al-Gahtani, and Almohsen; Investigation, Alsugair, Alsanabani and Aljarallah; Methodology, Aljarallah, Al-Gahtani, Alsanabani; Project administration, Alsugair, Almohsen, and Al-Gahtani; Resources, Alsugair, Almohsen, and Al-Gahtani; Software, Aljarallah, Alsanabani; Supervision, Alsugair, Al-Gahtani, and Almohsen; Validation, Aljarallah, and Alsanabani, and Al-Gahtani; Visualization, Alsugair, Aljarallah, and Al-Gahtani; Roles/Writing – original draft, Aljarallah, Alsanabani, and Alsugair, Writing – review & editing, Alsugair, Aljarallah, Alsanabani, Almohsen, and Al-Gahtani.

Disclosure statement

No conflicts of interest exist. The submitting author is responsible for the co-author's interests.

Data availability statement

The raw data supporting the findings of this paper are available on request from the corresponding author.

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APPENDIX

Table A1. Identified WCs of the housing infrastructure construction projects

No.	WC name	No.	WC name
1	Client's slow response and slow decision-making mechanism	33	Delay in delivery of materials to the site
2	Problems in the ent's organization, such as bureaucracy and lack of specialists	34	The problem resulted in interference among different subcontractors
3	Delay in running bill payments to the contractor or consultant	35	Delay of regulatory reporting
4	Client's unique needs, such as additional work and change order	36	Execution errors that lead to rework
5	Deficiencies and changes in project scope	37	Poor evaluation of contract items, tendering documents, and quantities, as well as poor scope definition
6	Contractor selection before the consultant	38	Inadequate modern equipment and low productivity level
7	Unfairness in tendering or method of contractor choice	39	Delay in dispute resolution or lack of dispute resolution procedure
8	Unqualified client's representative	40	Poor distribution of personnel
9	Starting execution before completing project documents.	41	Material waste due to poor design or poor execution
10	Lack of project financing	42	Familiarity with site conditions, location, and project complexity
11	Delay in reviewing or approving design documents	43	Delay due to administrative approvals
12	Delay in sample approvals, inspection, and making a decision	44	Poor site safety
13	Unqualified consultants, lack of consultant experience in design, supervision, and quality control	45	Inadequate specifications and shortage of design data
14	Poorly integrated organization structure for consultant	46	Changes in ca ore team
15	Inadequate contractor experience	47	Language barriers
16	Impact of lack of wastage management plans	48	Variations of actual quantities of work compared with quantities to bidding documents and underestimation of cost

End of Table A1

No.	WC name	No.	WC name
17	Impact of lack of site management	49	Supplying poor-quality materials
18	Impact of design changes and revision, which cause wastage of materials	50	Complete familiarity with systems and laws in KSA
19	Impact of not adhering to rules and regulations	51	Conflicts, poor communication, and coordination among contractors and other parties
20	Lack of funds influences wastage in construction	52	Unavailability of qualified sub-contractors
21	Wastage due to excessive material used more than what is required	53	Truthfulness of contractor or consultant to get a significant gain
22	Impact of improper handling of material	54	Side effects due to project activities
23	Impact of lack of stores on sites	55	Scheduling errors and actual execution duration are more significant than the duration in the tender
24	Wastage due to damage of material during transportation	56	Inadequate definition of authority or responsibility, as well as supervision overlapping
25	Insufficient training for workers	57	Force majeure such as (Flash Flood, non-seasonal floods, Earthquake, Fire, wind damage, lighting, soil conditions, and landslides)
26	Unavailability of skilled labor	58	Severe weather conditions, such as the impact of cold weather conditions
27	Impact of lack of cooperation between contractor and his laborers	59	Fluctuations in the prices of resources (materials, labor, etc.)
28	Impact of lack of supervision and material control that causes wastage	60	Unforeseen/unpredictable site conditions such as soil conditions, groundwater, etc.
29	Impact of unsafe working conditions	61	Accidents at the construction site
30	Poor management team performance, such as late requests for inspections or poor site management	62	Material theft and vandalism that cause material wastage
31	Workers' problems, such as inadequate motivation or improper accommodations	63	Impact of change in govt. authority instructions/ policy that causes material wastage
32	Unskilled workers and poor labor productivity		

Table A2. Identified QCs of the housing infrastructure construction projects

No.	QC name	No.	QC name
1	Scope of the project (type and nature)	19	Skill and experience of supervision staff
2	Impact of poor assessment of the project site	20	Skill experience of contractor's staff
3	Complex execution of the project	21	Lack of communication between supervision and contractors' staff
4	Project duration	22	Lack of consultation with the client by the Contractor Team
5	Incompleteness and inconsistency of design documents	23	Lack of timely decisions and corrective actions by the contractor team
6	Drawings not prepared in full detail	24	Errors and omissions in design documents
7	Drawings not prepared in full detail	25	Lack of communication and coordination within the contractor site team
8	A contractor caused the delay	26	Unsafe practice at a site (lack of safety conditions on site)
9	Lack of planning and management by contractor	27	Change in schedule
10	1Poor quality of contractor's work	28	Change in schedule
11	Execution errors by contractor	29	Lack of supervision
12	Misunderstanding/non-cooperation between contractor & supplies	30	Lack of finance
13	Climatic impact affects the quality of construction	31	Frequent changes in design
14	Improper storage handling system	32	Faulty pre-project survey
15	Does overtime affect the quality of the project?	33	Delay in obtaining permission from regularity authorities
16	Lack of communication between supervisors and laborers affects construction quality		
17	Dose morale and attitude affect the quality of the project		
18	Negligence of equipment maintenance		