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Dynamic modeling to reduce the cost of quality in construction projects

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ABSTRACT

In the construction industry, the primary concern of project-based organizations is how to achieve a balance between the optimal level of quality and the associated costs. The cost of quality (COQ) can help to achieve this balance. COQ in construction projects are dynamic in nature and hence should be considered as a complex interrelated system rather than a set of separate individual factors. This research aims to model the complex system of cost of quality and present policies for the reduction of those costs in construction projects. To implement the proposed model, the system dynamics approach is used to determine the impact of prevention and failure costs on the COQ and to analyze designed policies. The qualitative model is created through the causal loop diagrams (CLD) and is analyzed quantitatively using the system dynamics approach for a case project. According to the research results, an increase in training hours and employing experienced labors will decrease the failure cost and will increase the prevention costs, resulting in a reduction in cost of quality. However, based on the simulation results, the use of labor with a higher work experience will provide the largest decrease in the cost of quality.

KEYWORDS

Cost of quality (COQ); system dynamics (SD); failure cost; prevention cost; construction industry; simulation

Introduction

Construction projects are complex and are implemented under uncertain conditions (Lee et al. 2005). Many construction projects fail to meet the pre-set goals in terms of cost, time, quality, and scope of work and are faced with the problems such as cost overruns, delays, poor quality and scope creep. Today, project quality management is of particular importance and the global competition has forced industries to pay more attention to the quality. Moreover, there are financial advantages gained through the adoption of effective quality management methods. (Duttenhoeffer 1992). Organizations today pay much attention to so-called quality management, since it refers to various management practices and processes that have positive impacts on the quality, cost, productivity, performance, and competitiveness (Li et al. 2017). In such conditions, it is necessary to reduce the cost of construction projects, while maintaining the expected minimum level of quality, to remain competitive in the market. Cost of Quality (COQ) in a project allows to quantify and document the quality of projects using the cost of quality analysis in order to make better and more efficient use of resources and invest in preventive and appraisal activities for reducing the project costs (Khaled Omar and Murgan 2014). Determining the costs needed to achieve quality and, in contrast, determining the costs of poor quality enables better cost control. Also, the managers can also make better decisions by gaining information about preventive measures and their consequences on the quality of outputs (Schiffauerova and Thomson 2006). Previous studies have shown that the efforts to improve quality lead to the increased product or service costs (Khaled Omar and Murgan 2014). In other words, quality improvement has its own costs. Therefore, measuring the cost of quality is very important, because it provides information on the cost of quality improvement programs (Khaled Omar and Murgan 2014). Cost of quality is an essential element of the total cost in any construction project. It is generally affected by several factors such as quality awareness of the project team, supervisory team experience, labor skills, design errors, material defects, quality improvement programs, accidents, and project duration (Tawfek et al. 2012). The purpose of COQ is to evaluate and highlight the benefits of quality improvement and its relationship with customer satisfaction and to link the benefits to the compliance costs in order to decrease the overall costs and increase the quality benefits (Iuliana et al. 2013; Alglawe et al. 2019). Companies generally have little awareness of the profit loss due to the poor quality. Smaller companies often have no budget for quality control and they do not try to control the cost of quality (Plunkett and Dale 1988; Abdelsalam and Gad 2009), but larger companies usually claim to evaluate the cost of quality (Abdelsalam and Gad 2009). In the construction industry, increasing attention has been paid to COQ since the early 1980s to improve the overall construction quality (Dyson and Chang 2005; Heravi and Jafari 2014). Therefore, attention to COQ in projects will reduce the total cost of the project while improving the project quality. However, it is essential to note that the attention to the COQ from a static point of view does not have the ability to determine the extent to which each factor impacts the COQ. The main objective of this paper is to identify various factors affecting the COQ in the construction projects from a dynamic perspective and to investigate their dynamic interaction using the system dynamics approach. Using the developed model, efficient policies can be designed and tested for reducing the costs.

The rest of the paper is organized as follows. A brief literature review with a focus on COQ is presented in the 'Literature review and background' section. Then, the 'Research Methodology' section presents the system dynamics approach and model structure.

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In the 'Dynamic Modeling of COQ Using Proposed System Dynamics Approach' section, the dynamic modeling of COQ is provided. Afterwards, the 'Case Study' section presents the alternative policies to reduce COQ and increase quality in a real project and then the simulation results are compared for different policies. Finally, the paper draws conclusions.

Literature review and background

In 1980, Crosby defined the concept of 'quality' as 'compliance with the requirements', referring to the need to assess compliance to ensure that the product complies with the requirements (Liepiņa et al. 2014). Quality is one of the most important features in the construction that covers all aspects of construction projects. Quality is the delivery of products and services so as to meet the reasonable requirements of owners, professional designers, and contractors in terms of compliance with contract requirements, prevailing industry standards, and permissible requirements (Engineers ASoC 2012). Quality is perceived as the ability to meet the requirements contracted with clients (Kazaz et al. 2005). If 'quality' is the endpoint, 'quality management' is the approach and process to achieve the quality. According to the 6th edition of the Project Management Body of Knowledge (PMBOK®) (Project Management Institute 2017), the project quality management process consists of three steps: quality management planning, quality management, and quality control. In the quality management planning as the most important quality management process, the quality requirements and/or standards for the project and its deliverables are identified and it is documented how the project will ensure compliance with the quality requirements and/or standards. One of the most important tools used in the quality management planning is COQ. Therefore, this study aims to perform a quality management analysis using the COQ tool. The concept of COQ can be traced back to the early 1950s. Dr Juran's first 'Quality Control Handbook' published in 1951 discussed the 'cost of quality' (Krishnan et al. 2000), which is one of the earliest quality measurement tools and has attracted the interest of many authors (Heravi and Jafari 2014; Nedeliaková et al. 2015). COQ can be defined as a measurement system that translates quality-related activities into a monetary language for managers, the sum of the costs needed to ensure that the quality requirements are met (Srivastava 2008; Alglawe et al. 2019). According to the PMBOK® standard definition, COQ includes all costs incurred during the product lifetime, including investing to prevent non-conformances, appraising the product or service for the conformance to requirements, and failing to meet requirements (rework) (Project Management Institute 2017). COQ is usually known as the sum of the conformance and non-conformance costs. The conformance cost is defined as the cost paid to prevent poor quality, and the non-conformance cost is defined as low-quality related costs resulting from the failure of the product or service (Schiffauerova and Thomson 2006; Heravi and Jafari 2014). The COQ analysis will improve activities through a combination of reduced costs and increased benefits of quality improvement. Therefore, a realistic estimate of the COQ and the resulting benefits - which is the balance between conformance costs and non-conformance costs – should be considered as an essential element and a critical issue for managers (Abdelsalam and Gad 2009; Kiani et al. 2009; Rema 2014). Since early 1980s, increasing attention has been paid in the construction industry to COQ for improving the overall construction quality (Dyson and Chang 2005; Heravi and Jafari 2014). COQ is an essential element of the total cost of any construction project. The purpose of COQ evaluation is to highlight the benefits of quality improvement and its relationship with customer satisfaction and to link the benefits to the conformance costs for reducing the overall costs and increasing the quality benefits (Iuliana et al. 2013; Alglawe et al. 2019).

After the introduction of COQ by Juran in 1950s, many researchers developed different methods and models for measuring the COQ. Some of these models include PAF (Prevention–Appraisal–Failure), Crosby Model, Opportunity Cost Model, Process Cost Models, and ABC Models. The PAF model is more popular among researchers and used in this study to analyze and evaluate the COQ. Feinberg classified the cost of quality into three accepted categories, namely prevention, appraisal, and failure (PAF) (Dimitrantzou et al. 2020). The prevention costs (PCs) are the key to improving the quality and minimizing the probability of non-conformances and errors (Kazaz et al. 2005; Abdelsalam and Gad 2009). In fact, the prevention costs are a key to profitability by preventing and reducing the non-conformances or failures through the quality planning activities, process control costs, design controls, training, R&D, certification and public management costs (Roden and Dale 2001; Ramdeen et al. 2007; Kiani et al. 2009; Malik et al. 2016; Alglawe et al. 2019). The appraisal costs (ACs) are the costs intended for complying with the requirements, including the activities such as test and inspection costs, maintenance costs, calibration, measurement, and test of equipment (Roden and Dale 2001; Kazaz et al. 2005; Ramdeen et al. 2007; Kiani et al. 2009; Moschidis et al. 2018). Construction quality assessment and control require a cost of 1% to 5% of total project costs on average (Ledbetter 1983; Kazaz et al. 2005). The failure costs (FCs) attempt to correct the non-conformances that occur before or after the delivery to the customer. The FC is classified into two groups of internal and external failures. The internal FC is incurred within an organization due to non-conformance or failure at any stage of the quality loop, such as waste costs, rework, re-testing, inspection, and redesign, while the external FC represents the costs incurred after delivering a low-quality product to the customer/user for the non-conformance or defect, such as repair costs, product returns, complaints, and claims (Alglawe et al. 2019). In the research conducted by (Kiani et al. 2009), the prevention and appraisal costs were investigated as the two group of costs affecting the quality using the system dynamics approach. The model presented in this research showed that the prevention costs have a greater impact on the COQ, particularly the cost of failure. Therefore, to achieve the expected quality level for the customer satisfaction, the prevention and appraisal costs should be considered. (Glogovac and Filipovic 2018) investigated the level of knowledge and maturity about COQ for the companies, including the manufacturing and service companies. The results showed that the companies that care about the specific requirements of ISO 9001 achieve better results in terms of the maturity of COQ management. Abdul-Rahman (1995) stated that the poor quality due to non-conformance during the construction leads to the increased project cost and duration. The non-conformance correction costs can be high and affect the company's profit margin and competitiveness. Construction companies can identify the non-conformance information using a quality cost matrix as a base case for the improvement. Li et al. (2000) modeled the impact of overtime and additional resources on the project cost and quality. The approach presented in this paper represents the first attempt to analyze the effects of overtime prescribing and adding additional resources on project cost and quality. The system dynamics model proposed in this paper is a useful way of capturing the interactions between process variables, which shows the effect of long-term work and overtime and additional resources on project cost and quality. Kazaz et al. (2005) investigated a mass housing project in Turkey. This project involved 3100 residential units that took more than four years to complete. The results of the research showed that the average COQ is 32.36% of the total cost of the project. They also stated that this value is very high compared to similar projects due to the low level of executive quality and the lack of contractors with international quality credentials. Abdelsalam and Gad (2009) studied a housing construction project in Dubai (UAE) involving the construction of 291 multi-story buildings. The result of this study showed that total quality costs averaged 1.3% of total project costs. On the other hand, the project failure costs accounted for 0.7% of total project costs. However, it was not possible to calculate the external failure cost group, because the projects under consideration had not yet been delivered to the client. The reason for this low amount of failure cost was justified by the fact that the client supervised the project on a daily basis with a project management team and a supervising consultant, which not only increased the accuracy of the contractors' work, but also reduced the inspection and prevention costs. In another research, Jafari and Love (2013) measured the performance of a quality management program over a 18-month period for a monorail project in Iran. The cost of quality system was implemented in this project and finally, the failure cost was calculated as 5% of the project contract value. Using the quality management program, about 2.78% of prevention costs and about 2.32% of contract value were allocated to the appraisal costs. The most important factor involved in the reduction of COQ in the failure sector was the use of full-time quality team and the repetitive nature of activities. The active performance management and inspection by the contractor resulted in the identification of errors and problems with pre-executed plans, leading to the improved quality management system performance and improved cost reduction mechanisms.

In research, Chopra and Singh (2015) formulated a decisive methodology to optimize COQ comprehensively. The result of this study shows that FCs have a direct positive correlation with COQ, and it increases with time. Further, FCs are inversely proportional to PCs and ACs. PCs and ACs act as independent costs, while FCs is a dependent or secondary quality cost. If the authors strategically allocate PCs and ACs in advance by using advanced statistical tools, then internal failure costs and external failure costs will diminish amply. Heravi and Jafari (2014) examined the quality-related activities through 77 structured interviews in 60 mass housing projects in Iran. In this study, a model for evaluating the COQ conforming to the studied projects was developed by fitting the third-order polynomial trend lines to the compiled data. Then, based on the developed model, the cost-saving capabilities were estimated for the optimized level of COQ. It seems that using this model to achieve the optimum level of quality costs can provide savings in the COQ and, thus, in total project costs. In research conduct by Al-Tmeemy et al. (2012) illustrates the contractors' perceptions of the importance of the quality cost system and the barriers that may constrain the implementation of the system for recording and collecting quality cost data. Lari and Asllani (2013) bring their focus on the relationship between the COQ and organization performance and introduces COQ as a central measure of organizational performance. This research has proposed a quality cost management support system (QCMSS) that enables an organization to better collect and analyze quality cost data. The result of their study shows that using quality costs as a performance measure for operational processes that can result in better performance for organizations.

In another paper, the quality management system indicators in some of the leading German companies were examined (Raßfeld et al. 2015). The issues such as high cost of information gathering, cost and benefit separation problems, lack of expected profits, lack of knowledge of the available methods, and difficulty in quantifying the quality benefit were assessed as the barriers to implementing the cost of quality (Raßfeld et al. 2015). Also Sawan et al. (2018) conducted a research on the quality cost of material procurement in construction projects. The result of this research showed that raising the prevention cost leads to the drop in failure cost and COQ in the project studied and the construction material procurement processes would benefit from a higher prevention cost.

In addition Rodin and Beruvides (2012), Kamal and Irani (2014), Lim et al. (2015), Peimbert-Garcia et al. (2016), and Czajkowski (2017) can be referred in relation to COQ. As can be observed, several studies have attempted to determine the effect of various factors on the cost of quality (Kiani et al. 2009; Wood 2012; Heravi and Jafari 2014). However, the complex factors of interrelated structure affecting the COQ have not been considered in the previous research. The previous studies have only examined the impact of one of the factors affecting the COQ and do not consider the interactive and simultaneous effects of various factors influencing the COQ (Ramdeen et al. 2007; Abdelsalam and Gad 2009; Kiani et al. 2009; Heravi and Jafari 2014; Glogovac and Filipovic 2018). As most of the methods used in COQ tackled the problem from a static point of view, such as Pareto and fishbone, the histogram was used to prioritize and analyze the COQ, but these tools do not pay attention to the dynamic relationships between the cost factors. The prevention, appraisal, and failure costs affect one another, and the investment in one of the components can change the other cost factors. The present study examines the COQ in a construction project from a dynamic/systemic point of view using the system dynamics (SD) approach.

System dynamics is a strong simulation method that allows to model and design complex systems. Despite the mentioned capabilities of the system dynamic models in dealing with the complexities and interactions among project components, according to the search conducted by researchers, the practical aspects of COQ by the system dynamics were properly addressed. System dynamics is capable of accounting for the complex interrelated structure of all the factors influencing the COQ.

Although SD has had several applications in project management (Li et al. 2000; Love et al. 2002; Lee et al. 2006; Nasirzadeh et al. 2008; Javed et al. 2018; Wang et al. 2018; Ansari 2019; Dabirian et al. 2019), there are very limited studies in which COQ has been studied using SD.

The literature review demonstrates that there is a research gap in previous COQ studies. Most of the previous studies have investigated one of the factors affecting the COQ; however, the simultaneous effects of different factors on COQ have not yet been studied. To overcome the shortcomings and fulfil the gaps, a system dynamics model was developed to simulate COQ in construction projects. The main contributions of this paper that differentiate it from previous studies are as follows:

- Design a new dynamic model for COQ in construction projects which accounts for the complex, interrelated structure of various influencing factors.

- Introduce a new model for effective quality management.
- Provide suggestions and policies to reduce COQ and increase project quality.

Research methodology

System dynamics approach

Systems dynamics developed by Forrester (Forrester 1961), is an object-oriented simulation tool that generates models of real-world systems and studies their dynamics. It allows to model complex systems considering all the influential factors (Khanzadi et al. 2012; Nasirzadeh and Nojedehi 2013). SD can consider the complexity, nonlinearity, and feedback loop structures inherent in physical and non-physical systems. The purpose of using system dynamics is to facilitate the understanding of the relationship between system behavior over time and its underlying structure and decision rules (Yuan et al. 2011). The SD modeling is useful for managing and simulating the processes with two important features: (1) It changes over time, and (2) It provides feedback-transferring and receiving information from the results (Nasirzadeh and Nojedehi 2013). The simulation enables the examination of 'what if' scenarios and the test of scenarios and policies for approaching a test environment, leading to the increased confidence in the implementation of specific policies and strategies (Richardson and Otto 2008). SD has also become a popular way of modeling different aspects of construction project management (Rodrigues and Bowers 1996; Li et al. 2000; Wang 2008; Nasirzadeh and Nojedehi 2013; Ding et al. 2018). According to the findings, the suitability of using SD to manage construction projects has been fully explored. For example, Rodrigues and Bowers (1996) proposed SD as an excellent tool for illustrating complex relationships, which may cause unexpected and excessive creep in the project. There are many other researchers that have highlighted the suitability of SD to model complex casual relationships (Love et al. 2000; Georgiadis and Besiou 2008; Ozcan-Deniz and Zhu 2016; Wang and Yuan 2017; Rostamnezhad et al. 2020).

Several graphical tools are used in SD to create system structure, including causal loop diagrams (CLDs) and stock-flow diagrams. In each causal link, a positive or negative polarity is created to indicate the type of change in the dependent variables as a result of the changes in the independent variables. Important loops are identified to resemble positive feedback loops (reinforcing) or negative loops (balancing) (Sterman 2000). In terms of the nature of data at the problem definition stage, the purpose of research using SD is to understand the dynamics of the problem and the reason behind this dynamic trend. It is a quantitative–qualitative research approach in which the tools such as the review of documents and expert opinions are used to collect qualitative data for explaining the dynamic hypothesis. In the next stages of research, namely model design and scenario analysis, the required data are more quantitative, and thus, the research approach is quantitative. As a result, it can be stated that this is a combined qualitative–quantitative research.

Vensim software package is used in this study for the formulation and simulation purposes. Vensim is a powerful tool for making communication and interaction between processes and problems. This tool allows the structure of a process or strategy to be linked to the dynamics (Ansari 2019). In this research, Vensim® software PLE version 7.3.5 was used.

Model structure

Figure 1 depicts the different stages by which the COQ is modeled using the proposed SD approach.

As shown, it is necessary to first identify all the factors affecting the COQ. Then, based on the identified factors and data existing in the case study, the qualitative model of COQ is constructed based on the CLD. Then, the interrelationships between the COQ factors are plotted in the form of stock-flow diagrams. A quantitative model of COQ is then developed using the mathematical equations. The dynamic simulation of COQ is performed using the developed quantitative model to determine the value of COQ. Afterwards, the model testing is a critical step in the modeling process to ensure that the model is correctly implemented according to the conceptual model. During the verification process, errors are revealed and fixed to generate the best model available to study the case in question while recognizing the model limitations. Therefore, in this research, five tests were applied to verify the SD model. Once the model is validated, alternative improvement policies can be tested to assess their impact on the improved COQ and finally, the best improvement policy can be selected. Therefore, by providing appropriate solutions and policies, contractors and clients can improve and reduce the COQ.

Dynamic modeling of COQ using proposed system dynamics approach

This section describes the steps involved in developing the proposed model of COQ using the system dynamics approach.

Identification of factors affecting cost of quality

COQ is affected by various factors that are either manageable or unmanageable. There are different ways to identify the factors affecting the cost of quality. One of the methods is the literature review. Hence, the usual factors affecting the cost of quality in construction projects are extracted from the literature as the first stage of the model and then, 22 major factors with high impacts on COQ are identified for the construction projects (Table 1). However, the first and foremost step is to determine the project factors under study. According to the document data available in the project and the interview with the project manager and quality manager of project under study, only four identified factors, *rework, in-service training, use of qualified labor and design* and *implementation of an incentive,* were proposed and selected to be simulated in the system.

Qualitative modeling of COQ

Several factors affect COQ, some of which are independent of each other and some of which may have complex interactions with other factors. Therefore, in this section, the complex structure of the impacts of COQ factors is modeled using the CLD (Figure 2). As shown, the arrows indicate the CLD relationships between the variables.

The positive and negative signals indicate that there is a positive and congruent relationship between two variables or a negative and opposite relationship. According to Figure 2, the relationships between the COQ components are shown on a large scale. The prevention activity can reduce the costs of appraisal and internal and external failures. In fact, there is a negative relationship between the costs of prevention, appraisal,

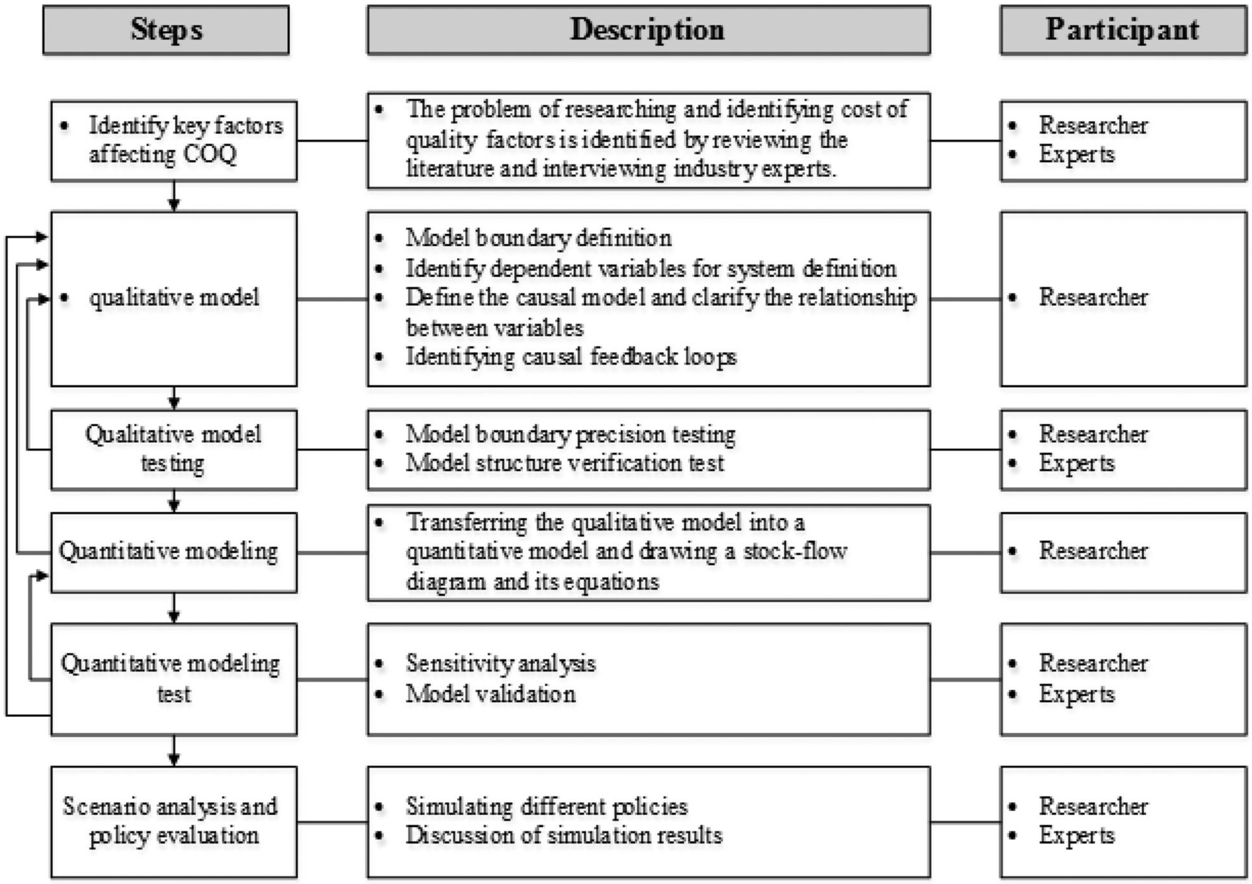

Figure 1. Research methodology: different stages of research using systems dynamics approach.

Table 1. Factors affecting the cost of quality.

Prevention cost	
• Project quality management plan	• Design and implementation of a motivational system
• Method of implementation and quality control	• Development and precision of control and measuring instruments
• Training	• Review contracts and documents
• Using quality workforce	
• Checking design progress in meeting the requirements	
• Evaluate contractors and suppliers	
Appraisal cost	
• Laboratory	
• Quality control labors	
• Assessment of external organization	
• Product and process evaluation	
• Measuring tools	
Internal failure cost	
• Redesign	
• Reworks	
• Reassessment due to rework	
• Cost of waste generated due to rework	
External failure cost	
• Complaints and claims	
• Penalties for poor quality	
• Costs of repair during the warranty period	
• Notorious for its poor quality	

and failure. Also, the appraisal costs have a negative relationship with the internal and external failure costs, which means that the costs associated with internal and external failures can be reduced by increasing the costs in the component of appraisal cost. Based on what is observed, there is a direct relationship between the PC, AC and FC and the COQ. As these costs increase, the COQ will increase.

The components of COQ investigated in this research

Figure 2 shows the interaction between the variables, but, in fact, the interaction between variables occurred by many factors and parameters in details. The COQ and the variable of costs are directly and indirectly influenced by several factors.

According to the main source for SD method (Sterman 2000), numerous tests have been used to validate the model, which are

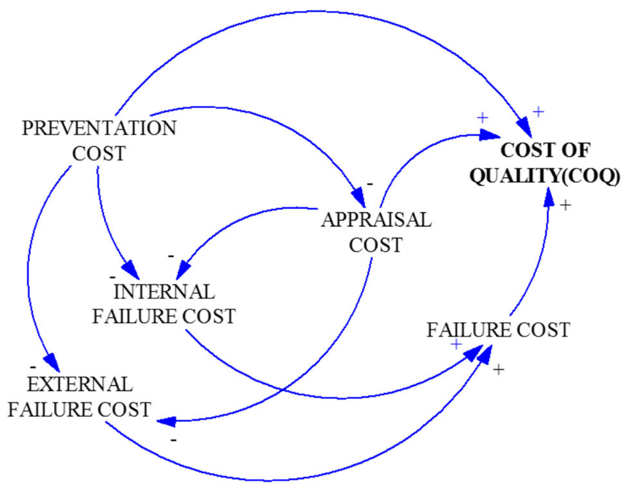

Figure 2. Conceptual diagram of interaction among COQ groups.

Table 2. Model boundary (endogenous and exogenous variables).

Endogenous variables (affected)	Exogenous variables (not affected)
Rework	
Error executing	
Fatigue	
Total labor	
labor productivity	Average experience of hired employees
planning pressure	Percentage of resignation rate
Skill rate	Job security
Experience labor	Interaction between employees
prevention cost	Authority
failure cost	Inflation
COQ	
Experience	
motivational system implementation	

mentioned in the model validation section. One of the tests is the model boundary, which identifies endogenous and exogenous parameters. Table 2 summarizes the scope of the model by presenting the most critical endogenous variables, which are the dynamic variables involved in the feedback loops of the system. They enable the exploration of the behavior patterns created by the relevant rules and the discovery of the way the behavior might change if these rules are altered. The model also contains several exogenous variables whose values are not directly affected by the system.

The qualitative model cost of quality in this research

After determining the parameters used in modeling, the CLD is constructed to better understand the system structure. Based on Figure 3, increasing the *executing error* leads to the increase of *unaccepted work*. As a result, there is a need to do more *rework*. Due to the identification of error, the amount of rework rises and for this reason, the scope of work increases, which increases the *work planned to do*. Consequently, *work in progress*, *completion rate*, *work done awaiting for acceptance* and *work done and release* increase. Eventually, *unaccepted work* will increase again in reinforcing loop R1. The reinforcing loop R2 can be described in a way that when the *Work done and release* increased, *accepted work* increased, but it has a reverse effect on the *plan of work to do* and decrease it. According to the remaining work in plan, the *total labor* can be determined. The number of labor has a direct effect on the *completion rate of work* and the increase in the completion rate causes *work done and waiting for acceptance* to rise. In R3 and R4, number of labor has a direct relationship with the *training* and *experienced labor* and the experienced labor improves the *skill* of workers. As a result, increasing the training and skill of worker has a negative effect on the *execution error*. There are two balancing loops B1 and B2 in the causal model of COQ in the construction project. The increase of *rework* was affected from *execution error* and *unaccepted work* and made a reverse effect on the *remained time* and decreased it. When the remained time decreases, it increases *planning pressure* and *consequently, weekly performance* and *fatigue of labor* increase, and as a result, execution error increases (B1). The increase in *Skills* causes the increase in the *labor productivity*, increasing *completion rate* and *work done and waiting for acceptance* (B2). In this model, it should be noted that labor productivity is also affected by *worker motivation*, and this parameter is affected by other parameters such as *Job security*, *Authority* and *Interactions between employees*. The results of the cause–effect diagram show the relationship between variables and in addition, shows the number of balancing and reinforcing loops. The reinforcing loops enhance the effects on another variable, while others have balancing and decreasing effects over time. Considering the CLD in Figure 3, it can be deduced that under the influence of parameters and their interactions, the costs of prevention and failure together provide the cost of quality. The prevention costs are the result of training costs, costs of using experienced and skilled labor, and costs of motivating the workforce, and the costs of failure are the result of total costs associated with rework, including the equipment cost, cost of human resources, duration of project, and waste of rework.

To make the model more comprehensive and user-friendly, the system was divided into four subsystems, including (1) rework, (2) using qualified labor, (3) motivational system implementation, and (4) training. Also, each subsystem can be divided into different sectors. These subsystems and sectors are interrelated in some of the shared parameters. They totally create a conceptual framework for the understanding and interaction between COQs in the project life cycle.

Figures 4–7 illustrate the COQ subsystems in the form of stock-flow diagrams. The COQ subsystems are briefly described below.

Rework subsystem

As shown in Figure 4, the dynamic model of the rework subsystem consists of four variables: ‘work done and waiting for acceptance’, ‘work release and accepted’, ‘re-work backlog’ and ‘error backlog’. The activities performed for the first time are carried out under a flow rate called the ‘completion rate’ and are accumulated in the ‘work done and waiting for acceptance’ stock variable. The process of quality control is done for all the activities carried out. If the activities performed have no failures or if they are not detected, they are the output of the ‘work done and waiting for acceptance’ stock variable under a process called ‘release rate’ and are aggregated into the ‘work release and accepted ‘stock variable’. If the work has defects and errors with the flow rate called ‘rate of error’, it is accumulated in the ‘error backlog’ stock variable. The errors during the construction are then compiled under the flow rate called the rework rate in the ‘re-work backlog’ stock variable. It should be noted that, in some cases, the rework may occur due to the changes in the design of the controlled and released work and is accumulated under a flow rate called the rework of accepted work rate in the re-work backlog stock variable. The activities accumulated in the ‘re-work backlog’ stock variable are also modified under the ‘re-work rate’ flow variable with time delays (1 month) and returned again to

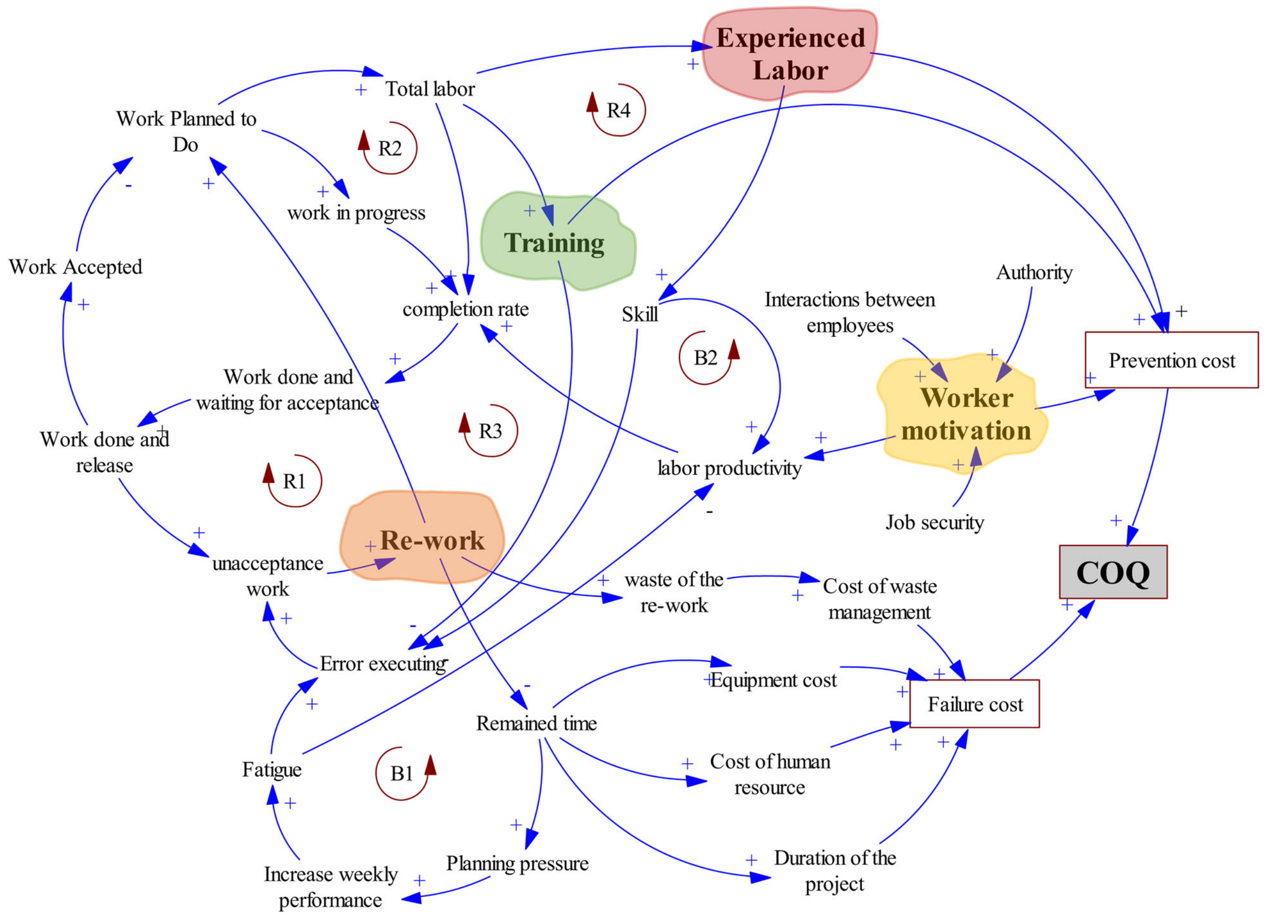

Figure 3. Casual loop diagram of factors affecting cost of quality.

the 'work done and waiting for acceptance' stock variable. The cycle mentioned above will continue until all activities are completed and no further errors are detected.

Motivational system implementation subsystem

One of the factors that may improve the project performance is the use of an appropriate motivational system for project staff (Figure 5). The motivational system implementation model is based on the amount of remuneration paid. In this model, the amount of remuneration paid comes from the contractor's financial ability to pay wages, which is affected by the contractor's collection of funds by the paid invoices. This model also uses other factors that influence the employee's motivation, such as job security, work authorization, appropriate interactions between employees, and paying without delay. The increase in employee motivation leads to the productivity improvement and consequently reduces the project errors.

Training in project implementation subsystem

Training is one of the factors affecting the prevention costs. Training will increase project staff skills. In the developed model, it is assumed that all the staff should be provided with the required training in the related fields. Therefore, all staff is required to complete at least 30 h of training during the project duration. In this model, the amount of training hours is considered as a stock variable, which is accumulated by the rate of training hours (Figure 6). Therefore, this subsystem consists of average hours of training, including the total number of training hours divided by the total number of labor in the project to determine the average number of training hours per person. It is also noteworthy that the increase in the hours of training will increase the staff skills. However, extra high training hours will not be cost-effective to reduce errors and reworks. This means that increasing the training hours indefinitely does not lead to zero errors and rework in the project, and thus, a maximum level of the average expected training hours is considered which is equal to 120 h. Any training above this amount will not decrease the errors in the project.

Using qualified labor subsystem

The qualified labor is a labor that has sufficient experience for project implementation. In this model, the worker experience is used as a factor that determines the quality of labors. As shown in this subsystem (Figure 7), two stock variables of 'labor' and 'experience' are considered to represent the quality of labors. In the labor-stock variable, the hiring rate enters the stock variable and the leave rate is the output. Three flow variables influence the labor experience, and the subsystem also assumes that the labor experience will increase throughout the project, since they gain work experience, thereby increasing their productivity. As a result of the labor leave, the experience gained from this project and the previous projects will be reduced. Also, it is assumed that the labor employed in the project has at least 12 months of experience.

Quantitative modeling of COQ. In the qualitative model of COQ, the relationships existing between various variables are specified,

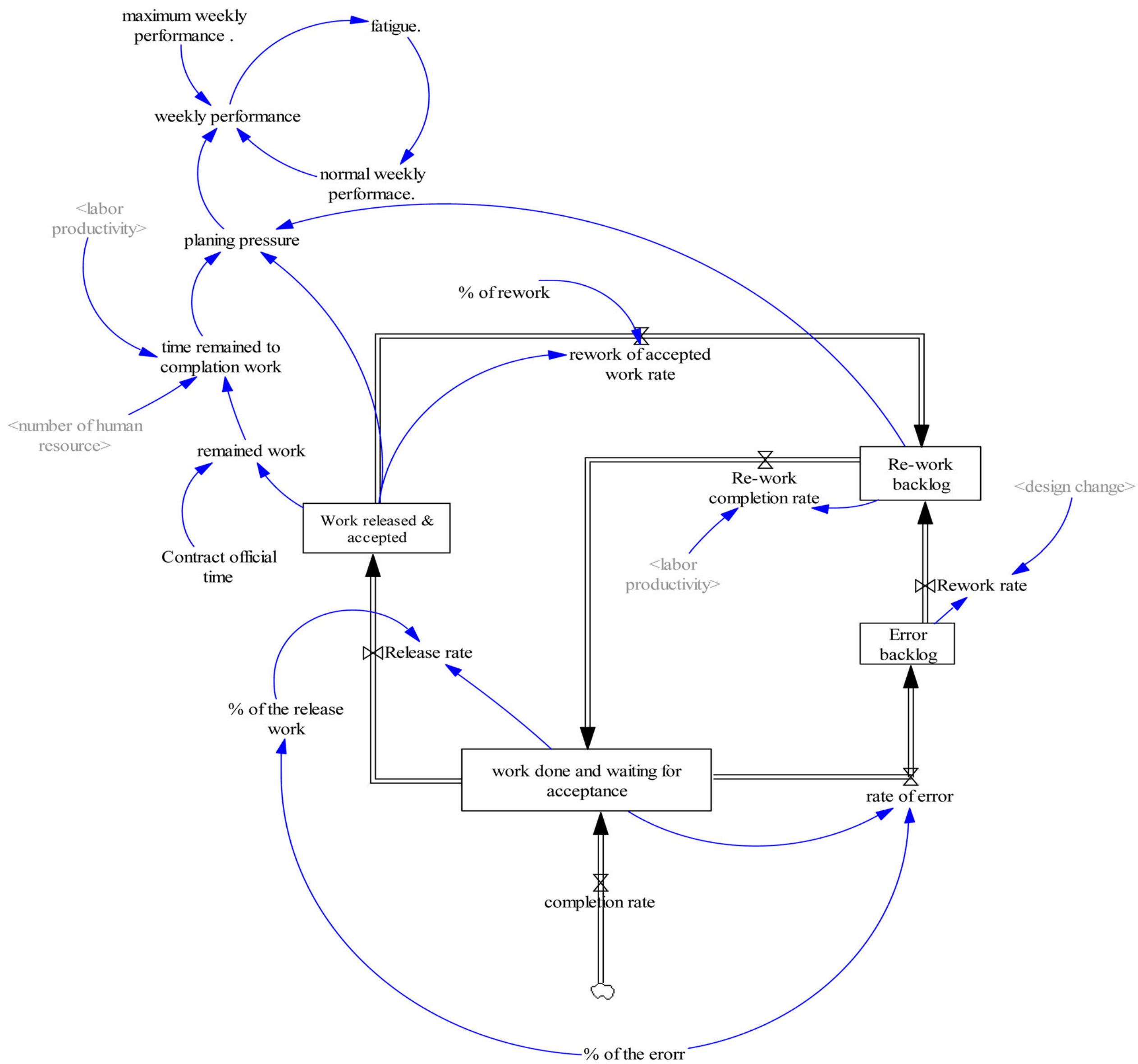

Figure 4. Stock-flow diagram of rework subsystem.

and the quantitative model of COQ is constructed using appropriate mathematical functions. The relationships between some factors are obvious and can be determined using simple mathematical equations, for example, the relationship between rework and failure costs or the relationship between the amount of experience and skill can be simply determined. However, the determination of these relationships and equations are not always simple and sometimes, they need to be extracted from historical data. For this purpose, it is necessary to analyze the historical data and determine the relationships among the factors through the regression. In this research, the parking construction project was selected as a case study and the historical data were collected for this sample project. The quantitative data required in this study were collected from existing project reports, documents, and records by gathering data from the site.

Case study

To evaluate the applicability and performance, the proposed model was implemented in a parking construction project located in Iran. This project is a 10-story car parking with a total floor area of 360,000 square meters.

The input information used to develop the simulation model are as follows:

- Contract duration: 400 days;
- Final project completion time: 560 days;
- Concrete volume: 360,000 m^3;
- Project cost: €17,857,143.

In the next section, COQ is simulated using system dynamics approach and the simulation results and policies are discussed.

Simulation results

This section provides a dynamic simulation approach that enables the decision-makers to model nonlinear and complex relationships existing among different parameters of COQ.

In the simulated model, based on the identified factors and the information collected from the case study, the estimated COQ at the end of the project is €1,743,857, which is 9.8% of total project costs. Accordingly, the costs associated with the

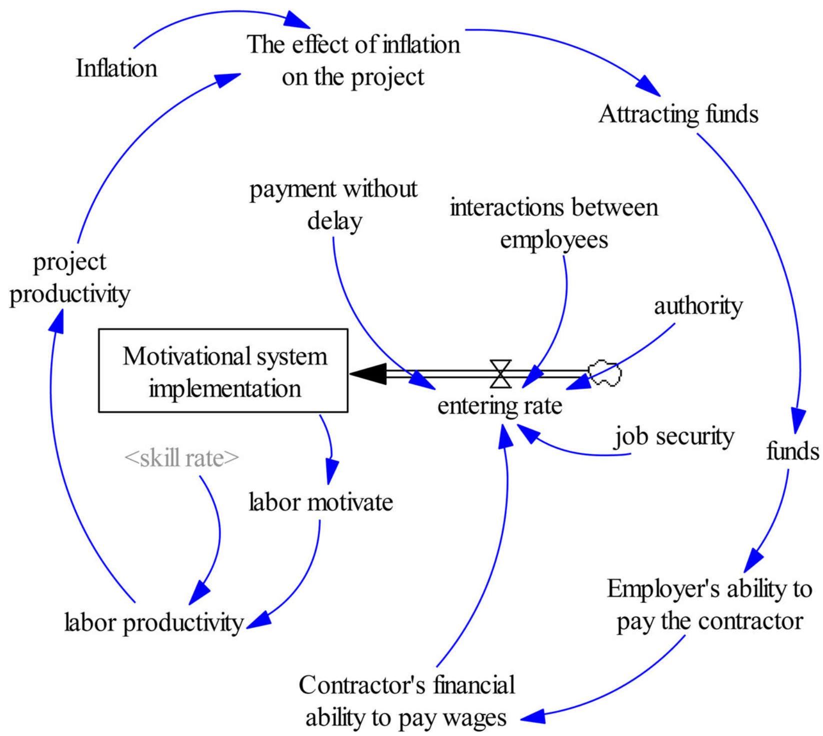

Figure 5. Stock-flow diagram of motivational system implementation subsystem.

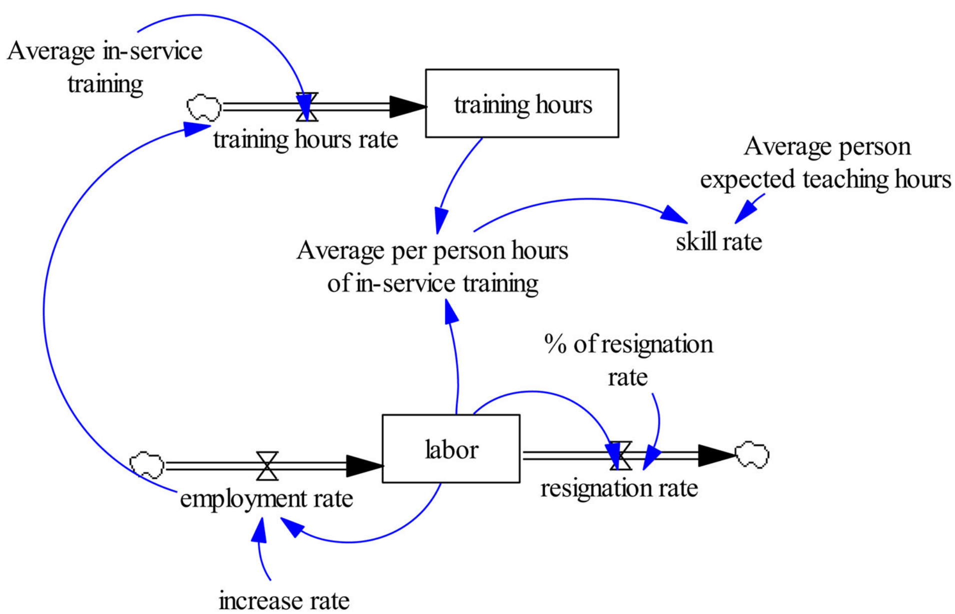

Figure 6. Stock-flow diagram of training subsystem.

prevention are estimated at €299,500, which is 1.7% of the COQ and the costs associated with the failure is €1,420,357, which is 8% of the COQ. Since internal failure costs are higher than the prevention costs, it is concluded that failure costs had the most significant impact on the cost of quality (Figure 8).

Moreover, based on the implementation results and according to the information obtained from the project, the rate of rework in the project increases until the fifth month, and then, it will have a decreasing trend (Figure 9). As shown in (Figure 9), this increase in re-work is due to the increase in the rate of errors at the beginning of the project because of design errors, changes in plans, contractor execution errors, and workforce fatigue during the project implementation. Also, as shown in the diagram, the rate of skill and rate of experience of labor increase as a result of training courses and labor participation in the project.

Model validation

The first question the researchers and modelers are faced with is whether a model is true and useful (Sterman 2000). Model validation demonstrates the model reliability for policy review and enhances the application credibility. Validation is a continuous process, and the present model was validated from the beginning of development to completion in various aspects. The validity tests of model are categorized into behavioral validation and

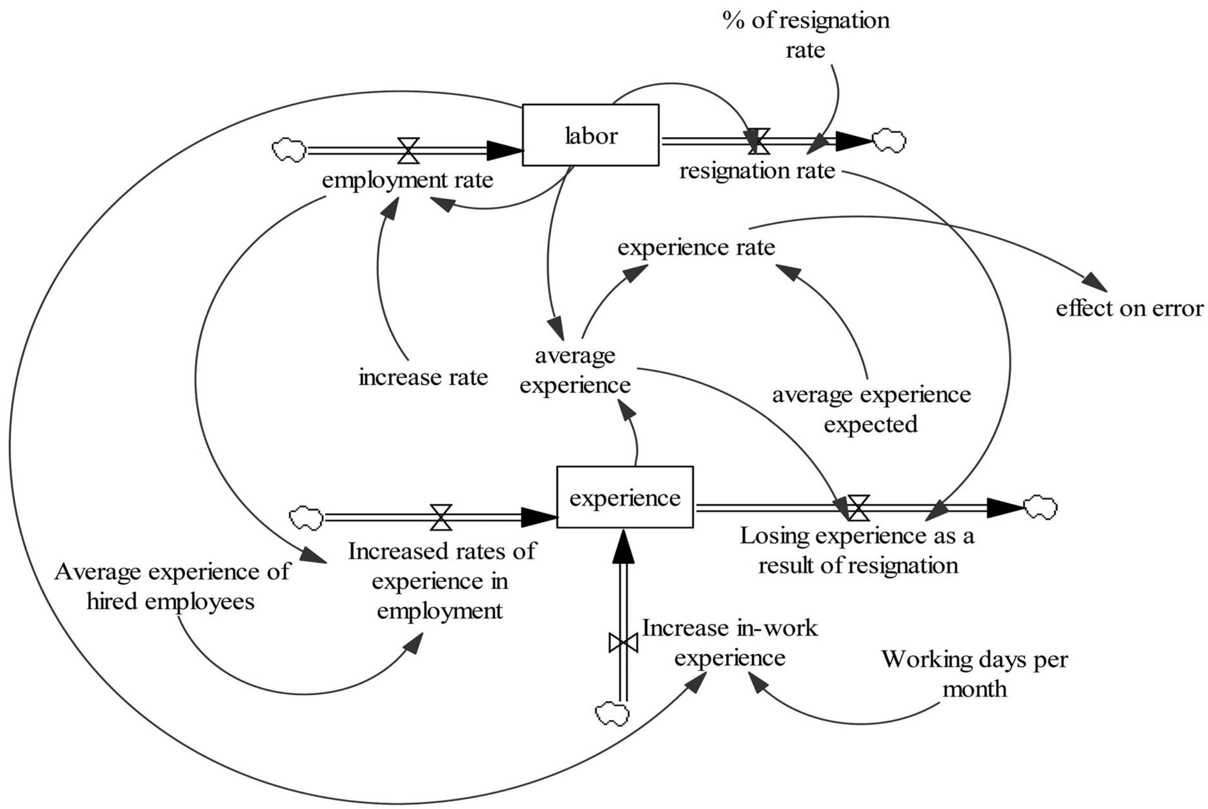

Figure 7. Stock-flow diagram of labor experience subsystem.

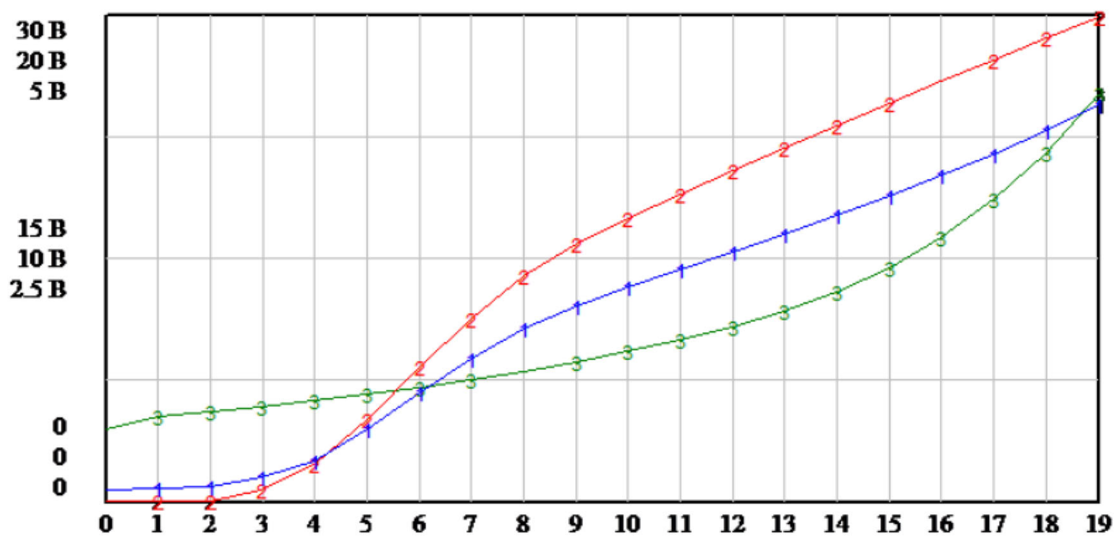

Figure 8. Comparison of costs of prevention, failure and quality of the case study project.

structural validation. The structural validity of the model is tested prior to the behavioral validity (Barlas 1996; Ansari 2019). The structural validity of the model is tested prior to the behavioral validity. When the model's structure is valid, the behavioral validity can be examined (Shi and Gill 2005). In order to build confidence in the model discussed in this paper, several structural and behavioral tests were performed based on the literature to validate the model results. These tests should always be related to the purpose of the project modeling (Sterman 2000), which, in this paper, is to assess the model ability to analyze the cost of quality in construction projects. This model was parameterized using different sources of information, which will be discussed in the following section of this paper. Initially, each equation was carefully inspected and its reasonability was proven. Testing the extreme value was conducted thoroughly by the simulation, checking whether the behavior of model is realistic without imposing the policies. For example, it was confirmed that *rework backlog* changes to infinite (i.e. very high value) if *the rework percentage of accepted work rate* sets to 100% or *labor productivity* sets to zero. The model ability to have historical behavior was checked. Checking the historical behavior helps the modelers to know whether or not the model output behave like the data from the real project (Nguyen and Ogunlana 2005; Etemadinia and Tavakolan 2018). The details of the historical behavior test

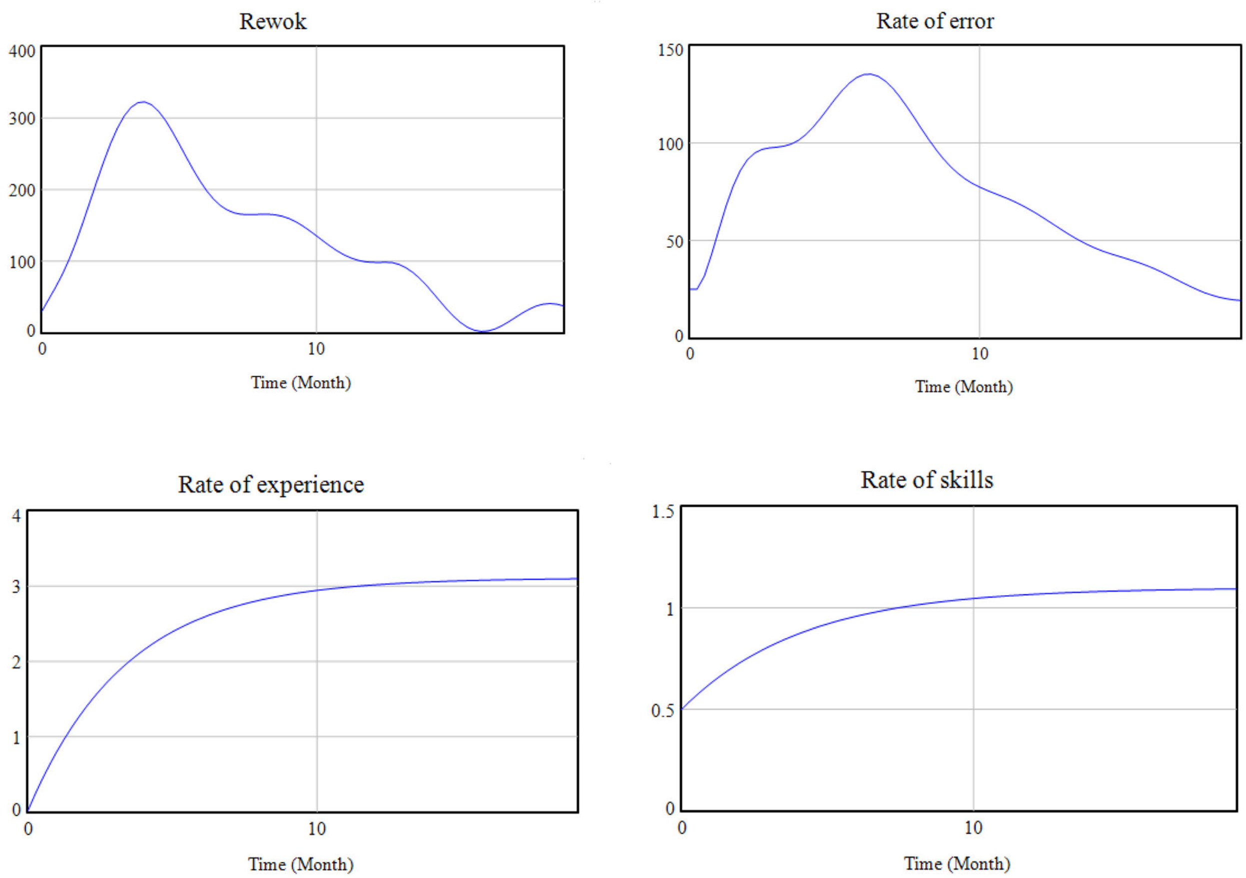

Figure 9. Comparison of rework, rate of error, rate of skill and rate of experience in the case study project.

Table 3. Summary of sensitivity analysis.

		Scenario		Sensitivity		
No.	Description	Best	Worst	Prevention	Failure	COQ
–	Base scenario	–	–	€ 299,500	€ 1,420,357	€ 1,743,857
1	Percent of rework of accepted work	0%	20%	0	135%	111%
2	Percentage of error	2%	50%	−22%	45%	39%
3	Average in-service training	100 h	0 h	38%	−19%	−9%
4	Average experience expected	60 months	2 months	158%	−45%	−10%
5	Labor productivity	3	0.3	17%	−17%	−11%

are provided by a case study in the following section. The results confirmed that the model can reproduce the historical behavior. With the direct inspection of the equations, every equation was checked to be dimensionally consistent without the inclusion of the arbitrary scaling factors that have no real-world meaning. Finally, the degree of sensitivity of the variables was analyzed. Sensitivity analysis examines whether the conclusion changes in ways important to the purpose when assumptions vary over the plausible range of uncertainty (Sterman 2000). The model behavior was measured in three primary dimensions of the paper object: COQ, prevention cost, and failure cost. The plausible range of uncertainty in the values of each exogenous parameter or the nonlinear relationship was first identified by estimating the best and worst case scenarios. The performance of the case study project for the likely scenario was: €1,743,857 for COQ, €1,743,857 for failure costs, and €299,500 for prevention cost. Model sensitivity is the percent of loss or improvement of project costs compared to the costs of the likely scenario due to the change in a single parameter's value from the likely scenario value. For example, in Table 3, when the *percentage of error* parameter increases from 2% (best scenario) to 50% (worst scenario), the COQ increases from €1,509,886 (best scenario) to €2,183,057(worst scenario). The COQ in the likely scenario (base scenario) is calculated as €1,743,857. The €673,171 change in COQ (2,183,057–1,509,886 =€673,171) represents a 39% sensitivity (673,171/1,743,857 = 0.386) in this parameter. The results of the sensitivity analysis show that while the behavior models of project objectives are insensitive to all the selected parameters, the sensitivity varies from one parameter to another. It was found that the prevention cost is insensitive to *rework percentage of accepted work* parameter and COQ and the failure cost has a high sensitivity in this parameter. The COQ, prevention cost, and failure cost are most sensitive to the following 5 parameters (Table 3).

Proposed polices

Based on the literature review and conducted interviews with the experts involved in the construction projects and COQ, several policies were determined and proposed to reduce the COQ in the project. These policies include increases staff skills through

Table 4. Comparison of cost variations in different scenarios of training hours.

Scenario	Skill rate	Prevention cost (€) (% of total project cost)	Failure cost (€) (% of total project cost)	COQ (€) (% of total project cost)
30 h training	1.09	299,500 (1.7)	1,420,429 (8.0)	1,743,857 (9.8)
50 h training	1.48	321,857 (1.8)	1,368,571 (7.7)	1,714,286 (9.6)
80 h training	2.07	356,286 (2.0)	1,291,857 (7.2)	1,671,714 (9.4)
100 h training	2.47	382,000 (2.1)	1,241,286 (7.0)	1,646,571 (9.2)

Table 5. Comparing cost variations in different scenarios of average project workforce experience.

Scenario	Experience rate	Prevention cost (€) (% of total project cost)	Failure cost (€) (% of total project cost)	COQ (€) (% of total project cost)
12-month experience	2.09	236,857 (1.3)	1,594,857 (8.9)	1,855,857 (10.4)
24-month experience	3.09	299,500 (1.7)	1,420,429 (8.0)	1,743,857 (9.8)
36-month experience	4.08	364,857 (2.0)	1,273,571 (7.1)	1,661,929 (9.3)
60-month experience	6.07	460,071 (2.6)	1,105,500 (6.2)	1,589,143 (8.9)

training, increased motivation and productivity, management waste due to re-work, reduced claims, and using experienced labors. Due to the time limitations of the research, only two policies were considered for testing, namely increase in training hours and use of experienced labor. The impacts of the policies on COQ were then evaluated.

Policy of increasing training hours and its impact on the cost of quality

One of the factors affecting the project COQ is staff training during the project. It is imperative for the staff to have training courses with specific time and content depending on the responsibility, type, and size of the project. Based on the information gathered from the project, an average of 30 hours of staff training was planned and held during the study period. In this policy, training hours were tested and evaluated in four scenarios of 30, 50, 80, and 100 hours of training. Increasing the training hours will increase the staff skills in this project. As staff training increases from 30 to 100 hours of training (from 1.09% to 2.47%), labor productivity increases. According to the simulation results shown in Table 4, the higher the training hours in the project, the higher the prevention costs and the lower the failure costs, which will reduce the overall COQ. As shown, with a 70-h increase in training hours, a 0.4% increase in the prevention costs and a 1% decrease in the failure costs are observed, and the overall COQ finally decreases by 0.6%. In fact, the researchers observed a 0.008% reduction in project costs per hour of training. Therefore, as training hours increase, the COQ will decrease, but this policy is effective up to a certain number of training hours and if the training hours exceed 120 hours, it will not affect the COQ anymore.

Policy use of qualified labor and its impact on COQ

The second policy adopted in this research was examined under four scenarios. Thus, based on the opinions of the experts interviewed, the people who started the project have an acceptable quality of service. Four scenarios of 12, 24, 36 and 60 months of work experience were tested for the policy review. According to the results provided in Table 5, as the experience of the labor employed in the project increases, the prevention cost will increase and the failure cost of the project will be reduced and consequently, the overall COQ will decrease. In the case of the fourth scenario, 60 months of work experience was compared with the first scenario with 12 months of previous experience. The 1.3% increase in the prevention costs and 2.7% decrease in the failure costs were observed. As a result, we will save 2.5% on COQ in the project. In fact, on average, each month of labor experience will save 0.05% on the project cost.

Discussion

Based on the simulation results achieved for the two proposed policies, the trend of the cost of quality and their variable were determined under each policy for different scenarios. In fact, the system is designed to reduce the failure costs in the project by increasing the prevention costs.

Two policies of increasing the number of training hours and increasing the use of experienced labors showed that both policies increase the prevention costs in the project and, consequently, reduce the failure costs. Based on the simulation results, it can be concluded that hiring experienced labor will have a more positive impact on reducing the COQ in the project and will save more cost. However, based on the results, if we hire a labor with average work experience of 12 months and increase the training hours, it may reduce the prevention costs compared to the policy of hiring a more experienced labor, but having 12 months of experience has a lower impact on reducing the failure costs and accordingly, the reduction in COQ is lower. This means that hiring more experienced labor in the project will be preventive and reduce the cost of failure in the projects, thereby reducing the project COQ that this result compliance with the (Mendes and Lourenço 2014) the lack of experience and education/training of workforces is the main reason for the poor performance of quality programs and increase cost-related.

Based on the results of this model, by increasing the prevention costs, the failure costs of the project will be reduced, thereby reducing the cost of quality by reducing the failure costs. This result is consistent with the past research in the literature (Juran and Godfrey 1999; Schiffauerova and Thomson 2006; Kiani et al. 2009; Chopra and Singh 2015; Sawan et al. 2018). Also, based on the results obtained in this study, a 1.3% increase in the preventive costs will result in a 2.5% decrease in COQ in the maximum case of 'hiring labor with 60 months of experience'. This is consistent with the past research conducted by (Roberts 1991) stating that 'by spending 1% more on prevention costs, the failure costs can be reduced from 10% of construction to less than 2%. Also, the model presented in this study can consider the dynamic nature of construction projects and simulate the exact amount of COQ.

Conclusion

Project cost management is an important competitive advantage for the core components of projects (owners and contractors). However, due to the complex nature of the project implementation conditions and the fact that most projects do not meet their cost and quality objectives, there is still a large gap in current cost control research and tools. One of the gaps along this path is the control of COQ in construction projects. While various tools for calculating the COQ do not incorporate the dynamics along this path, including the feedbacks, delays, and nonlinear relationships, they are not adequately included in the analysis and policymaking. Projects are complex and dynamic systems that cannot fully understand their behavior and improve their performance without dynamics, nonlinear relationships and feedback between the factors. Therefore, in this study, due to the complex structure among the factors affecting the COQ, a system dynamics model was used based on previous research to evaluate the cost-effectiveness of some quality management policies.

In this study, the factors affecting the cost of quality were first identified through the literature. Due to the wide range of factors and the lack of sufficient information from the COQ identified in the project, out of the 22 identified factors, only four factors used. 'Re-work', 'motivational system implementation', 'training', 'use of qualifying labor' were used in this system. Since the factor data for the appraisal cost and external failure costs did not exist in the project, only the costs related to the prevention costs and internal failure costs were used in the model. The complex interrelated structure of different factors affecting the COQ was modeled using CLD and the qualitative model of the COQ was constructed.

In this paper, an integrated SD model was designed to analyze the effect of future performance on the decrease of COQ by proposing the policies. In order to validate applicability and performance of the proposed SD method in the COQ, a real case was selected at a parking construction project in Iran. The proposed policies included increasing training hours and use of qualified labor. The results of the simulation illustrated that investing in training and employing experienced labors can reduce the failure costs and increase the prevention cost and consequently, the COQ in the project can be reduced. The results of the system dynamics model demonstrate its capability to effectively decrease the COQ, so that based on the simulation results, by increasing the hours of training, there will be an increase in the prevention costs and decrease in failure cost and total decrease in COQ. Also, by employing qualified labor with more experience, there will be an increase in prevention costs and decrease in failure costs. As a result, there will be a decrease in COQ. Given the simulation results, the use of experienced labors has the greatest impact on the decrease of COQ in the project. However, in addition to employing more experienced labor in projects to benefit from the world's up-to-date knowledge, it is necessary to provide training but with fewer hours.

The proposed SD approach offers a flexible and robust method for the simulation of COQ with the possibility of finding the root causes of the increase in COQ. It is noteworthy that this research focused on the internal failure cost and prevention cost; therefore, external failure costs, appraisal cost, and some constraints are beyond the model boundary. However, the model presented in this study can be integrated with other methods such as optimization to improve policy and model responses. Since more prototype projects are needed to validate model outputs, it is recommended to use this model in other construction projects, including the road, bridge and dam. It is also recommended that future model development works to be done in order to identify all or most factors affecting the COQ.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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