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Modeling quality management in construction projects

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Abstract

This research presents a dynamic mathematical system for modeling and simulating the quality management process in construction projects. Through sets of cause and effect feedback loops, all factors that internally and externally affect the quality management process are addressed. The proposed system integrates fuzzy logic with system dynamics simulation scheme to consider the uncertainties associated with the model parameters and estimation of the extra cost and time due to quality defects. Quantification of the consequences of the quality failures is performed based on the α-cut representation of fuzzy numbers and interval analysis. The proposed approach is efficient in modeling and analyzing a quality management process which is complex and dynamic in nature and involves various uncertainties. The proposed approach is implemented in a real submarine water supply pipe line project in order to evaluate its applicability and performance. The negative impacts resulting from quality failures are simulated. These negative impacts are mitigated by the implementation of alternative solutions.

Keywords: *Fuzzy logic, Modeling, Quality management, Simulation, System dynamics.*

1. Introduction

Quality can be defined as meeting the legal, aesthetic and functional requirements of a project. In a general statement, quality is obtained if the stated requirements are adequate, and if the completed project conforms to the requirements [1].

Existence of an inefficient quality management (QM) process increases the possibility of non-conformance to project requirements. The process by which an item is made to conform to original requirement by completion or correction is defined rework [2]. A construction industry development agency defines rework as "doing something at least one extra time due to nonconformance to requirements" [3]. The direct costs of rework in construction projects are considerable and have been found to be more than 10% of contract value [3-5].

There are multiple interdependent factors affecting the actual impact of quality deviations (rework). The traditional approaches did not account for the inter-related structure of the influencing factors. To evaluate the actual impact of quality deviations (rework) in a project one should look at the project from a systems perspective [6-8]. By taking a systems perspective, the numerous inter-related components affecting the quality management process are considered through the various cause and effect feedback loops. Moreover, the highly dynamic nature of quality management process throughout the life cycle of the project resulting from the multiple feedback processes is accounted.

Ford and Sterman [9] were among those who modeled the rework cycle in a product development process using system dynamics (SD). System dynamics introduced by Forrester [10], is an object oriented simulation methodology which accounts for various interactive cause and effect feedback loops.

Love et al. [6] implemented SD in a qualitative manner and determined the causal structure of rework influences in construction. Lee et al. [11] developed a framework for quality and change management to identify the iterative cycles cause by errors and changes.

The cited researches, however, face some major defects. The previous researches did not account for the imprecise nature of the influencing factors and their vague inter-dependencies or commands. They employed SD in a deterministic environment and did not account of uncertainties in system behavior. However, due to the imprecise and uncertain nature

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of many factors affecting the QM process, traditional deterministic system dynamics is not an appropriate modeling tool. It is therefore necessary to extend the system dynamics approach to take account of the uncertain variables.

Furthermore, previous researches have only considered the QM process in an isolated environment. The external interactions which may exist between the quality deviation problems (reworks) and other potential risks such as inflation, pressure to crash project duration etc. have not been considered (Fig. 6). This is an important consideration since the existence of external interactions may intensify the overall impact of quality failures due to indirect and secondary effects caused by other risks that are present. Finally, in previous studies, the values of input factors affecting the QM process have been assigned based on individual estimates without considering the values of other factors which affect them.

This research emphasizes two important issues in the quality management of construction projects, which have not been considered in previous works. Firstly, we identify and integrate existing uncertainties in construction quality management into the modeling structure using a fuzzy logic approach. Secondly, the external interactions between different risk items are embedded into the modeling structure by defining appropriate feedback loop structures to account for possible intensification of the overall impact of quality failures due to the indirect and secondary effects of all other existing risks.

Therefore, this paper presents an approach which integrates and implements a system dynamics simulation approach with fuzzy logic to produce a powerful tool for quality management in construction projects. This proposed tool considers the uncertainties associated with model parameters and the estimation of extra cost and time due to quality defects. A system dynamics simulation approach is employed to model the external interactions between quality deviations and other potential risks. Hence, the full impact of quality failures can be simulated. A fuzzy logic based quality prediction system (a fuzzy inference mechanism) is developed and used to predict the values of different input factors affecting the QM process as presented below. The consequences of quality failures are simulated for the achieved fuzzy number of input factors by the proposed integrated fuzzy-SD simulation approach. Quantification of the consequences of the quality failures is performed based on the α-cut representation of fuzzy numbers and interval analysis. The negative impacts resulting from quality failures are mitigated by the implementation of alternative solutions. Finally, the proposed methodology is implemented on a real water supply project in order to assess its applicability and performance.

2. Dynamic quality management

Effective quality management (QM) plays a vital role in the successful planning and execution of construction projects. An efficient QM process may reduce the possibility of mistakes, changes and omissions, which in turn reduces conflicts and disputes [1], [12].

In this research a SD based approach is used to model the complex structure of a QM process arising from internal and external interactions. The proposed SD based quality management system simulates the consequences of quality failures on project cost and time. A high level diagram for the proposed dynamic quality management system is presented in Fig.1. The dynamic quality management system benefits from 4 different modules each simulating part of the overall process. As presented in Fig.1, the proposed dynamic quality management system combines (1) a quality prediction module, (2) quality management process simulator module, (3) external interactions simulator module, and (4) a dynamic construction project process simulator module. These 4 modules are integrated to simulate the effects of quality failures on projects cost and time. Interactions of the modules and their function in the overall simulation process (including inputs to and outputs from each module) are presented below briefly.

The "quality prediction system" is employed to determine the values of two input parameters affecting the quality failures consequences (i.e., probability of flaw and probability of flaw exploration). The complex inter-related structure of different factors affecting the quality management process internally and externally is then modeled using the "quality management process simulator module". The "external interactions simulator module" is employed to simulate the exacerbating effects of other risks which have external interactions with the quality failure problems (rework). Therefore, the overall impact of quality failures could be assessed. In order to simulate the quality failure consequences, the proposed model of quality management process is incorporated into a dynamic construction project process simulation model (CPPSM) which has been developed using system dynamics

The proposed dynamic quality management system simulates the consequences of quality failures on project cost and time. Moreover, using the proposed SD model, alternative solutions which may be implemented for mitigation of the negative impacts resulting from quality failures are simulated. So that, the cost and time benefits of implementing alternative solutions is simulated. The different modules of the proposed dynamics quality management system are explained in more detail in the following sections.

2.1. Quality prediction system

The existence of non-conformances in a task may lead to rework. The amount of rework is influenced by two factors: (1) the probability that a task is flawed and (2) the probability that the flaw is explored by the implemented quality management process.

The quality prediction system aims to predict the values of these two input parameters based on the values of various influencing factors. The values of these two factors will be predicted by the use of the fuzzy inference mechanism. The resulting values, which are fuzzy probabilities, act as an input to the simulation of the quality failure consequences (reworks) in the later stages.

As shown in Fig.2, the “probability of flaw” is influenced by four factors including labor experience, complexity of work, repetitiveness of tasks and schedule pressure [10], [11]. Having more experienced labor improves the quality of work

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leading to a decrease in the probability of flaw. As the complexity of work increases, the probability of flaw will also increase. The third factor affecting the probability of flaw is the repetitiveness of a task. If a task is composed of repetitive work units, the probability of the flaw decreases as the workers become more familiar with the task through repetition. Finally, schedule pressure is the fourth factor affecting the probability of flaw. Schedule pressure is defined as the ratio of the time required to complete the project to the time available until the project completion date. An increase in schedule pressure will

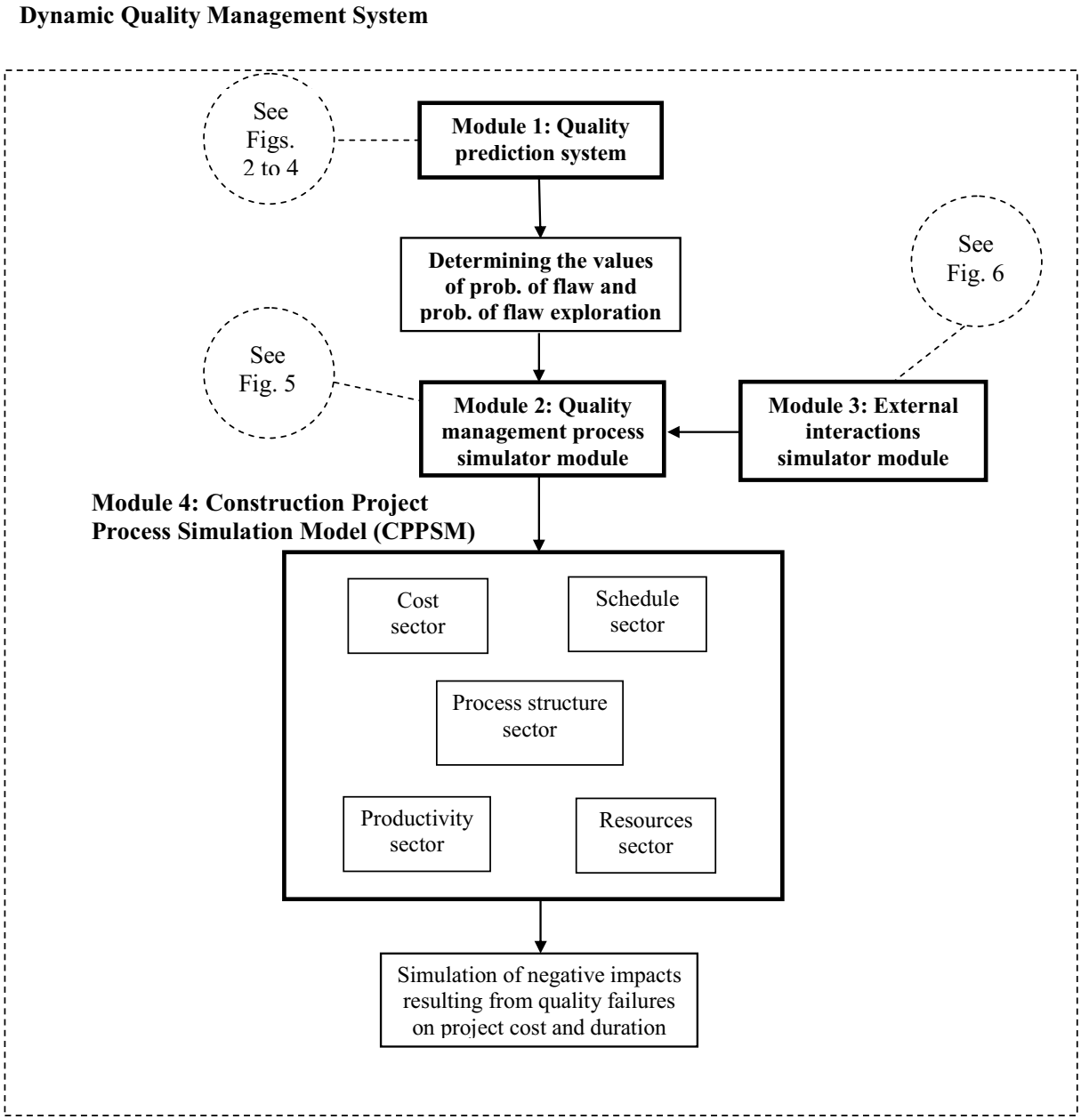

Fig. 1 High level diagram of dynamic quality management system

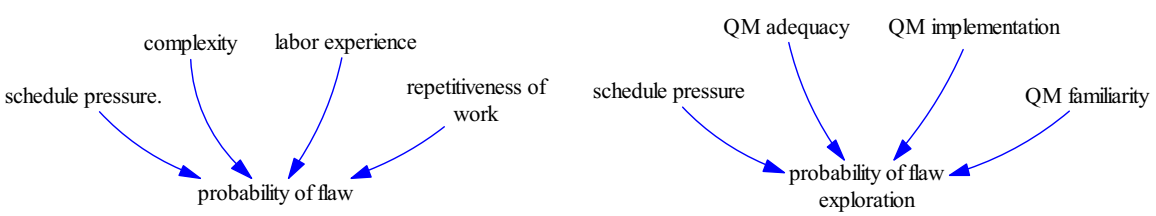

Fig. 2 Conceptual model of input parameters affecting the quality management process

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decrease the quality of work. Hence the probability of flaw will increase accordingly.

Similarly, the "probability of flaw exploration" is influenced by four factors including QM implementation, QM familiarity [11], schedule pressure [10], [11] and QM adequacy. QM implementation is measured by the ratio of quality management labor applied to the quality management labor required. The familiarity of supervisors on the project with the implemented QM technique is the second factor affecting the probability of flaw exploration. The third factor is schedule pressure which decreases the probability of flaw exploration. As supervisors work faster to meet the schedule, the probability of flaw exploration will decrease accordingly. The final influence on "probability of flaw exploration" is the QM adequacy.

The value of different influencing factors affecting the "probability of flaw" and the "probability of flaw exploration" are not normally known with certainty (Fig. 2). Furthermore, it is difficult to define the relationship between the values of the influencing factors and the system outcomes (i.e., the probability of flaw and the probability of flaw exploration) as they have vague and imprecise dependencies.

Fuzzy logic introduced by Zadeh [13] is highly suited to consider these types of uncertainties. Fuzzy systems handle incomplete or imprecise data in applications including prediction. It provides an efficient approach to model future outcomes of a system by considering ambiguous and imprecise data in a manner similar to human judgment functions.

Fuzzy logic "if- then" rules perform approximate reasoning with imprecise or vague dependencies or commands [13].

Therefore, in this research a process using fuzzy inference is developed to address the ambiguous and imprecise relationships between the influencing factors and the "probability of flaw" and the "probability of flaw exploration". In Fig.3, a standard "Mamdani" style inference mechanism which has been applied in this work is shown [14].

The developed forecasting method consists of three major components including fuzzification of input variables, inference and defuzzification (Fig.3) [15]. In order to use a fuzzy inference engine, the input data must be transformed to a linguistic form. This process is called fuzzification. Fuzzification module defines the membership functions (MBFs) for each input and output variable. The values of input and output data are fuzzified using MBFs to determine their degrees of membership to the corresponding linguistic terms. In Fig.4, the membership function graphs of different input factors and output variables (i.e., the "probability of flaw" and

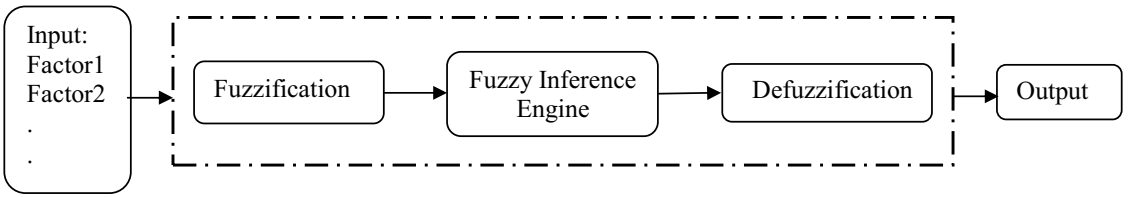

Fig. 3 Schematic representation of fuzzy inference system (developed forecasting method)

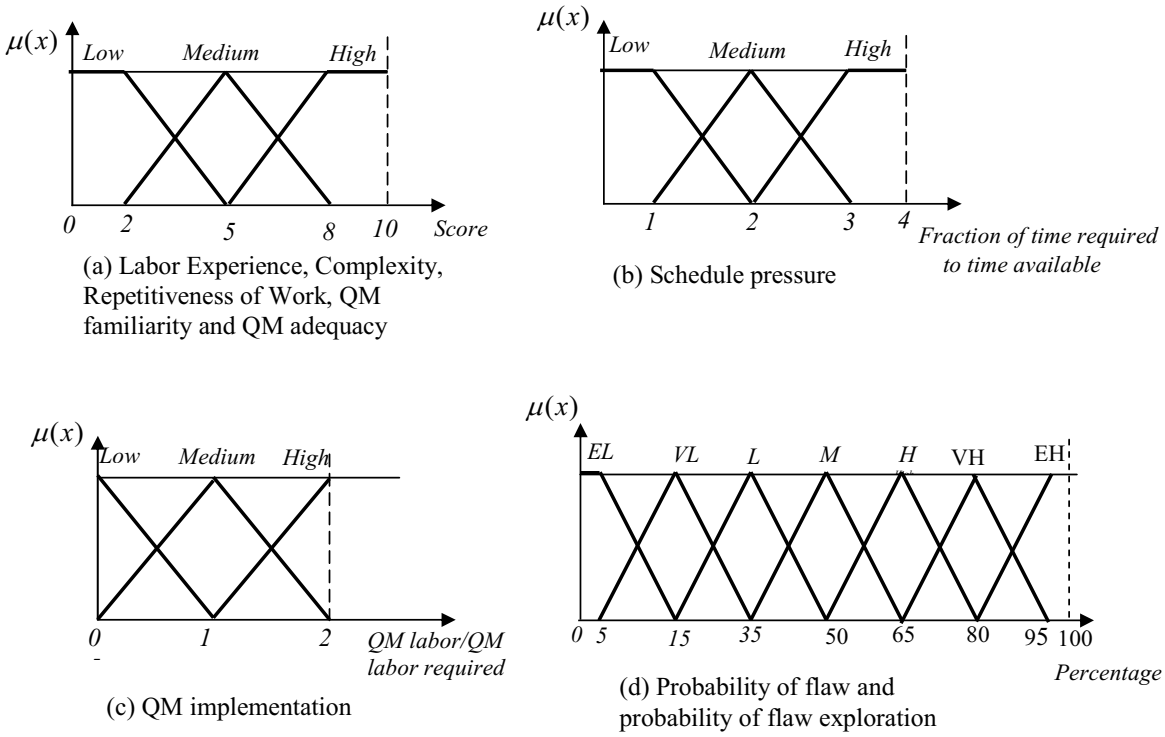

Fig. 4 Membership functions of different factors affecting the QM process

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the "probability of flaw exploration") are shown. Linguistic terms such as low, medium and high are utilized to represent input and output variables for the developed model.

The number of terms of each linguistic variable and the shape of the membership functions depends on the expert opinion and is generally selected by using the human/expert experience, intuitively. It should be stated that the number of terms in input and output linguistic variables may partially affect the output variable of FIS which in turn will affect the final outputs of the proposed SD model. The fuzzy inference system identifies the rules that apply to the fuzzified values of input variables and deducts the output linguistic terms that describe the status of the outcomes. A set of fuzzy rules has been developed to assist in forecasting the values of the two input parameters affecting the quality management process, i.e., (1) the probability of flaw and (2) the probability of flaw exploration. Table (1) shows the inference rules for the "probability of flaw". There exists a total of 3^4=81 fuzzy control rules. As an example, rule 1 is expressed as:

If labor experience=high, complexity of work=low, repetitiveness of work =high, and schedule pressure=low, then probability of flaw=extremely low.

Before elaborating on the last design step, which is the choice of an appropriate defuzzification procedure, we show how input values trigger the computation of the control action. The computational core can be described as a three-step process consisting of (1) determination of the degree of membership of the input in the rule-antecedent employing the minimum operator as a model for the "and", (2) computation of the rule consequences or fuzzy implications using the minimum operator and (3) aggregation of rule consequences to the fuzzy set "control action" using the maximum operator [15].

Finally, the output of the inference process is transformed to a crisp value using a defuzzification method. Defuzzification will not be carried out at this stage as the fuzzy number of the "probability of flaw" and "probability of flaw exploration" achieved by the inference mechanism will be given directly as an input to the SD simulation model in order to produce the quality failure consequences by a fuzzy number.

2.2. Quality management process simulator module

After determining the factors affecting the QM process using the fuzzy inference mechanism, the consequences of quality failures are simulated by the system dynamics approach. Figure 5 presents a conceptual diagram of the quality management process. As shown, there are numerous factors affecting the QM process internally through the recognized cause and effect feedback loops. The conceptual model presented herein, is based on the model proposed by Ford and Sterman [9] which was originally developed for product development projects. Their model has been modified to consider all influencing factors affecting the values of input parameters acting as an input for the simulation of the QM process, i.e., the probability of flaw and the probability of flaw exploration.

The quality management process model consists of three stocks (variables that represent stored quantities and characterize the state of the system) entitled “work waiting for quality management”, “work checked and released” and “rework”. The work is done for the first time through the "initial work rate" flow and is accumulated in the “work waiting for quality management” stock. It is obvious that there is no guarantee that all the work is performed correctly. The quality management process would be implemented at this stage to detect any flawed task. The "probability of flaw" and the "probability of flaw exploration" predicted in the previous stage, help to determine the portion of work which has been performed correctly and the portion of work which is flawed and must be re-executed.

During the quality management process, the tasks which are found to be flawed pass through the "discovering flaws rate" flow into the "rework" stock. The flawed tasks that accumulate in the "rework" stock are re-executed and returned to the “work waiting for quality management” stock. The tasks for which no flaws have been detected accumulate in the “work checked and released” stock. These tasks may be performed correctly or they may have undiscovered flaws. The undiscovered flaws represent tasks containing as yet undetected errors. They are therefore perceived as being checked and released. However, these errors may be detected, often few months later downstream, where they become

Table 1 Fuzzy inference rules for probability of flaw

Labor experience	Complexity of work	Repetitiveness of work								
		H			M			L		
H	L	EL	VL	L	VL	L	M	VL	L	M
H	M	VL	L	M	L	M	H	L	M	H
H	H	VL	L	M	L	M	H	L	M	H
M	L	VL	L	M	L	M	H	L	M	H
M	M	L	M	H	M	H	VH	M	H	VH
M	H	L	M	H	M	H	VH	M	H	VH
L	L	L	M	H	M	H	VH	M	H	VH
L	M	M	H	VH	H	VH	EH	H	VH	EH
L	H	M	H	VH	H	VH	EH	H	VH	EH
		L	M	H	L	M	H	L	M	H
		Schedule pressure								

Abbreviations:
EL: Extremely Low, VL: Very Low, L: Low, M: Medium, H: High, VH: Very High, and EH: Extremely High.

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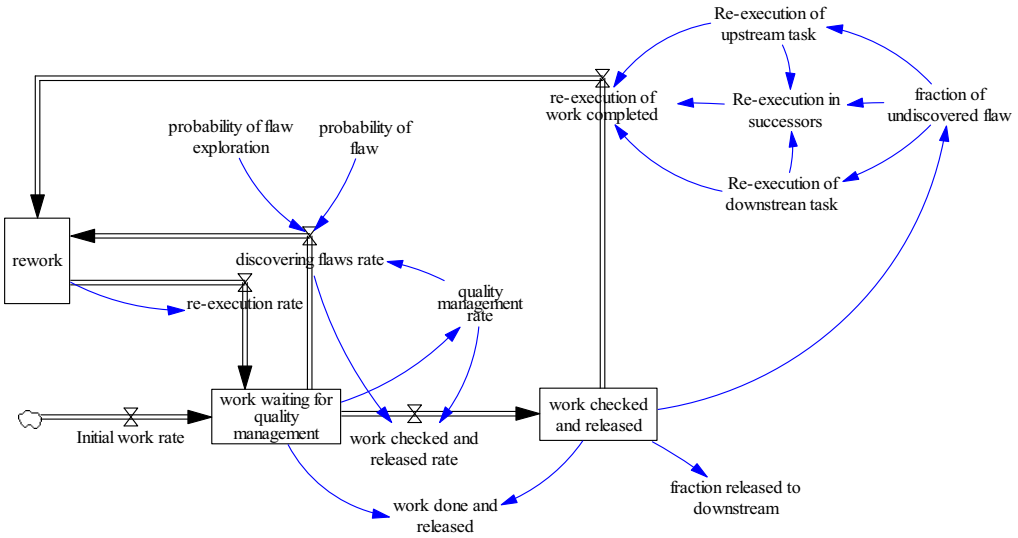

Fig. 5 Conceptual diagram of quality management process model

"known rework". The undiscovered flaws may cause the re-execution of upstream tasks, re-execution of downstream tasks and also re-execution in the successor tasks due to the external interrelationships that exist between the flawed task and their predecessors and successors (Fig. 5). The re-execution of work that has been completed can bring a huge additional amount of rework in the last stage of a project which may cause a project failure. Errors may occur again while performing the task for the second time (rework), and hence the work can cycle through the quality management process several times as the project progresses.

2.3. External interactions simulator module

External interactions may result in the emergence of new risks or may exacerbate the impact of the existing risks [16-18]. Hence, the overall impact of quality failures may be intensified.

The conceptual diagram of external interactions between the quality deviation problems (reworks) and other potential risks is depicted in Fig.6 Four risks with external interactions are identified as: (1) contribution of the local community, (2) inflation, (3) underestimation of construction costs and (4) pressure to crash project duration. A detailed modeling of each of these risks can be found in Nasirzadeh et al. [16-18].

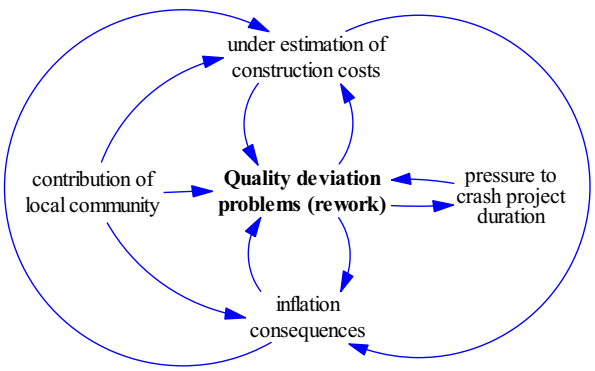

Fig. 6 Conceptual diagram of external interactions between quality deviation problems and the other potential risks

The different risks depicted in Fig.6 will intensify the negative impacts of rework due to their external interactions with this risk. As an example it is conceived that "contribution of local community" will affect the risk of rework. In the project case example explained hereinafter, it is anticipated that the client may ask the contractor to provide some portion of the required labor from the local community. In this case, the average experience (workmanship) of the workers decreases and the probability of flaw increases accordingly. Hence, the amount of rework increases which will exacerbate the amount of project cost overruns and project delays.

2.4. Simulation of negative impacts resulting from quality failures

In order to simulate the quality failure consequences, the proposed model of quality management process is incorporated into a dynamic construction project process simulation model (CPPSM) which has been developed using system dynamics [16-18]. The CPPSM acts as a baseline in order to assess the negative impacts of quality failures (Fig. 1). The CPPSM is extensively large and captures all the dynamics and feedback loops involved in the construction process, particularly those surrounding the rework cycle. Hence, the negative impact of quality failures could be simulated. The CPPSM includes the cost sector, schedule sector, resources sector, productivity sector and process structure sector [15], [16], [17]. CPPSM can simulate the project outcomes in terms of time and cost. Therefore, the quality failure consequences on both cost and time performance measures could be simulated.

3. Application of the proposed methodology

The proposed dynamic quality management system was employed in a water supply project in order to assess its applicability and performance. This project is a real submarine pipeline project intended to provide the required drinking

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water of an island from the coastal city through a pipeline executed on the seabed. The base cost and duration of the project was estimated as 12 millions dollars and 15 months, respectively. The base case assumes that the entire work is performed correctly. In reality, however, some portion of work may be performed incorrectly. Existence of these non-conformances will cause major negative impacts in terms of project delays and project cost overruns.

In this section, the additional expenditures caused by quality failures are quantified by employing the proposed dynamic quality management system (fuzzy-SD approach). Then the negative impacts caused by the quality failures are mitigated by the implementation of alternative solutions.

As an input to the simulation system, the "probability of flaw" and the "probability of flaw exploration" for different tasks of the project are estimated. These probabilities are assessed through the use of the quality prediction system explained in section 2.1. For this purpose, the values of different influencing factors affecting these two probabilities were proposed by experts involved in the project based on their subjective judgments. The values of the "probability of flaw" and the "probability of flaw exploration" were then assessed by the fuzzy inference mechanism. As an example, the values of different influencing factors affecting the "probability of flaw" and the "probability of flaw exploration" for one of the project tasks, namely "pipeline fabrication" is presented in Table 2. In this task, the pipeline is fabricated by welding pipe segments in the workshop located on the beach. It was assumed that a radiographic test is used as the quality management technique to inspect the welding quality. Using the proposed quality prediction system, the values of the "probability of flaw" and the "probability of flaw exploration" for the "pipeline fabrication" task were determined as (0.12, 0.21, 0.24) and (0.60, 0.70, 0.88) respectively, where (a,b,c) represents a triangular fuzzy number achieved by the quality prediction system. The values of these two probabilities for the other tasks of the water supply project were assessed similarly.

The consequences of quality failure on the project objectives were quantified employing the proposed fuzzy SD approach. To simulate the quality failure consequences taking account of uncertainties in the input variables (i.e., the "probability of flaw exploration" and the "probability of flaw exploration"), the traditional deterministic system dynamics approach was extended to become non-deterministic using Zadeh's extension principle. Extension principle states that if f: R*R→R be a binary operation over real numbers, then it can be extended to the operation over the set R of fuzzy quantities.

This involves the associated crisp values of fuzzy numbers of "probability of flaw" and the "probability of flaw exploration" being used as an input to the simulation model with the outputs of the system also defined as a fuzzy number. Considering the extension principle, the quantification of consequences of the quality failures is performed by a method based on the α-cut representation of fuzzy numbers and an interval analysis. The consequences of the quality failure defined by a fuzzy number are determined as follow:

(1) Select a particular α-cut value, where $0 \leqq \alpha \leqq 1$. (2) The associated crisp values of the fuzzy number of the "probability of flaw" and the "probability of flaw exploration" corresponding to α is determined as $[a_\alpha, b_\alpha]$. (3) Dynamic simulation of the system is performed by CPPSM with these crisp values as input to the simulation model. Since the crisp inputs to the SD model depend on the selected α-cut, the output of the simulation model is valid for the same value of α–cut (4) Steps 1-3 are repeated for as many values of α needed to refine the solution. Covering the entire range of α–cut results in a fuzzy number as the output of the model. The consequences of quality failures on the project cost and duration performance measures are presented in Fig. 7. The impacts of quality failure on the project objectives have been determined for both the net impact and the full impact. The net impact shows the direct consequences of quality failures in an isolated environment

Table 2 The values of different factors affecting the QM process for "pipeline fabrication" task

Influencing factors on probability of flaw	Value	Influencing factors on probability of flaw exploration	Value
(1) labor experience	7	(1) QM implementation	(1,1.5,2)
(2) Complexity	2	(2) QM familiarity	7
(3) repetitiveness of work	8	(3) QM adequacy	8
(4) schedule pressure	(1,1.5,2)	(4) schedule pressure	(1,1.5,2)

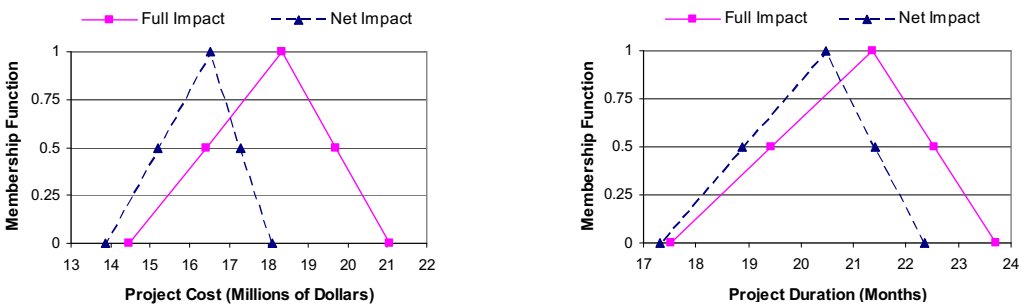

Fig. 7 Fuzzy number of quality failure consequences on project cost and duration

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while the full impact considers both the direct and indirect impacts of quality failures on the project objectives. As explained, in the case of full impact, due to the existence of indirect effects caused by external interactions, the overall impact of quality failures is intensified (Fig. 7). The left and right values of the resulting fuzzy number of QM failure consequences will present the under-estimated and over-estimated values of the QM failure consequences, respectively.

Using the center of area method for defuzzification, project duration and cost changed from the base case (i.e, 15 months and 12 millions dollars) to 20.1 months and 16.16 millions of dollars for the net impact and 20.9 months and 17.96 millions of dollars for the full impact, respectively.

Four alternative solutions, namely: (1) using more experienced labors, (2) change in quality management technique, (3) overtime policy, and (4) hiring new labor/equipment are tested for mitigation of negative impacts caused by the quality deviations.

In order to evaluate the impacts of alternative solutions, the qualitative model of different solutions is constructed using cause and effect feedback loops. The inter-relationships between variables that constitute the feedback loops are assessed by appropriate mathematical functions. The impacts of alternative solutions on project cost and duration are quantified by the comparison of system behavior resulting from CPPSM with and without alternative solutions.

The impacts of four alternative solutions were assessed by the proposed fuzzy SD approach. Using more experienced labors (UMEL) was the first solution implemented to reduce the value of the "probability of flaw" for different tasks of the water supply project. As an example, for the "pipeline fabrication" task, the "labor experience" index was increased from 7 to 9 using more experienced welders. As a result, the "probability of flaw" was decreased from (0.12, 0.21, 0.24) to (0.07, 0.16, 0.20). However, using more experienced labors imposed additional costs on the project. A change in QM technique (CQMT) was the second solution implemented to mitigate the negative impacts of quality defects. In this case, the implemented QM techniques were changed to reduce the value of the "probability of flaw exploration" through increasing the values of "QM familiarity" and "QM adequacy". As an example, for the "pipeline fabrication" task, the "QM familiarity" index was increased from 7 to 9 by changing the implemented QM technique (i.e., from radiographic to ultrasonic test). As a result, the "probability of flaw exploration" was increased from (0.60, 0.70, 0.88) to (0.65, 0.77, 0.93).

By implementation of an overtime policy (OTP), the average number of hours worked each week (workweek) was increased (by 25%) which led to an increase in productivity and therefore the negative impacts of quality failure on the project duration were mitigated. However, if workweek exceeds normal workweek, there will be a negative side effect on project performance due to labor fatigue which in turn increases the amount of human errors. Hence, the "probability of flaw" will increase accordingly.

In the case of hiring new labor/equipment (HNLE), the amount of current labor/equipment was increased (by 25%). Therefore, the productivity was increased accordingly and the negative impacts of quality failure on the project duration were mitigated. However, if the amount of labor/equipment exceeds a case dependent maximum value, this will have negative impacts on productivity due to the lack of working area available.

The implementation of UMEL, CQMT, OTP, and HNLE will also mitigate the negative impacts on other items which have external interactions with quality defects such as inflation and "pressure to crash project duration" risks (Fig. 6). Hence the total impact of the four alternative solutions on all of these inter-related risks have been simulated. Considering all nominated risks, the range of cost and duration were determined as (16.21, 23.37) million dollars and (19.02, 26.35) months, respectively. In Fig. 8, the impacts of the implementation of UMEL, CQMT, OTP, and HNLE policies on the project objectives have been depicted. It should be note that since CQMT had a minor impact on the project cost and duration, it has been assumed that a combination of UMEL and CQMT policies are implemented simultaneously.

The implementation of OTP and HNLE reduced the project duration more than "UMEL+CQMT" (Fig. 8). The implementation of HNLE decreased the project duration more than OTP. The reason for this is that the negative impacts of the lack of working area in the case of HNLE are less than the negative impacts of labor fatigue in the case of OTP.

Project cost decreased when implementing "UMEL+CQMT" more than it did for the other two options (i.e., OTP and HNLE). For both HNLE and OTP, project cost did not increase from the base case although the negative impacts of fatigue and lack of working area were present. The reason for this is that when implementing OTP and HNLE, the project duration decreased intensively and consequently the major negative impacts of inflation risk on the project cost were reduced. The implementation of HNLE reduced the amount of cost overrun more than OTP due to the same reason explained above for project duration.

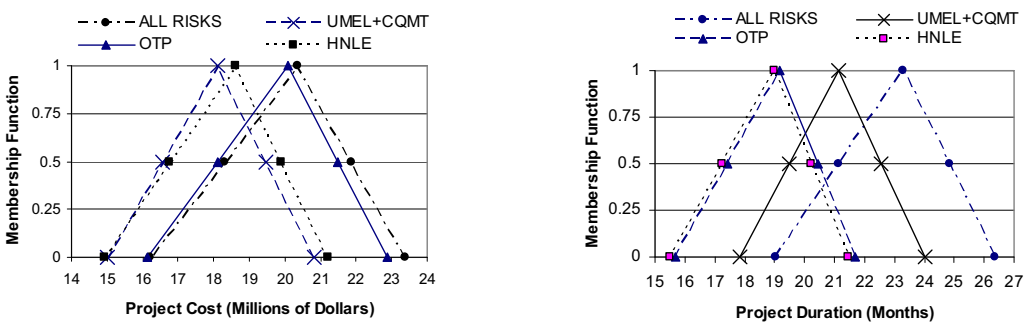

Fig. 8 Fuzzy number of alternative solutions impacts on project cost and duration

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The above process allows the decision maker to compare the effectiveness of different alternative solutions. Using the simulation results, he may decide on the most appropriate alternative solution before implementation.

4. Conclusions and remarks

This paper presents a system dynamics (SD) based simulation approach to model and simulate a quality management process in construction projects. The proposed approach overcomes many of the shortcomings of previous works in the area of quality management.

The proposed approach employed SD in a non-deterministic environment. The uncertainties in system behavior were accounted for by integrating fuzzy logic with the SD simulation approach. The values of different input factors affecting the QM process were predicted by a fuzzy logic based quality prediction system (fuzzy inference mechanism). The QM process was modeled in a non-isolated environment. It was shown that the existence of external interactions may intensify the overall impact of quality failures due to indirect and secondary effects caused by other risks.

The proposed methodology was employed in a submarine water supply pipeline project in order to evaluate its applicability and performance. The overall impact of quality failures was determined by fuzzy numbers. The resulting fuzzy numbers that depict the possibility distribution of the overall impacts enable a project manager to quantify the quality failure consequences at different confidence levels. These overall impacts were significantly intensified when their full impact was accounted for by considering the indirect effects caused by the external interactions. The negative impacts resulting from quality failures were then effectively mitigated by the implementation of alternative solutions.

The proposed methodology offers a powerful simulation tool for quality management in construction projects. The consequences of quality failures as well as the efficiency of alternative solutions can easily be assessed prior to their occurrence. Employing the proposed integrated fuzzy-SD approach, the project manager may decide on the most appropriate alternative solution in order to mitigate the negative impacts of quality failures during the early stages of a project.

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