Case Study

Dynamic Simulation Model for Project Change-Management Policies: Engineering Project Case

Ramin Ansari[1]

Abstract: The management and control of megaprojects are incredibly complex. Difficulties occur due to unexpected changes and errors. To effectively manage disruptive changes, reworks, and errors, project managers are required to consider the dynamic behavior of feedback loops that cause delays and disturbances. The system dynamics (SD) modeling approach has been used in the past few decades to address this need for the analysis and improvement of project performance. This paper discusses how changes in dynamics can influence the performance of a project. The SD model was utilized to improve project planning and simulate change-management policies for an Iranian project in the petrochemical industry. This study contributes by developing a dynamic simulation model for effective formulation of project change-management policies by taking into account the time, cost, quality, resource, and financial indicators. The model enables the decision maker to compare alternative change-management policies, e.g., funding, outsourcing activities, schedule adjustment, and labor control in terms of project performance indicators. Aided by a case study and an SD methodology, a comparative analysis of change-management policies was provided. Results indicated that resource planning has an essential role in the project performance improvement. **DOI: 10.1061/(ASCE)CO.1943-7862.0001664.** *© 2019 American Society of Civil Engineers.*

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Introduction

Designing reliable project plans is a complicated procedure. It is mainly because unforeseen events happen during the execution phase, i.e., changes and errors in the design or estimations may disrupt the initial plan and cause resource conflicts. It is usually recognized by project stakeholders that change effects are challenging to measure and quantify. Therefore, improving the performance of the project schedule requires an innovative decision support system that accurately monitors activities and the corresponding progress, predicts potential resource conflicts, and reallocates resources in such a way that negative consequences are minimized.

This research was motivated by the problem of change management in the Iranian construction industry. The problem was investigated by a case study of an engineering project executed by Industrial Projects Management of Iran (IPMI). IPMI was established in 1971 under the name Tabriz Housing Company with the aim of constructing residential buildings. In 1987, based on the decisions taken by the shareholders, the scope of the activities of the company exceeded the scope of construction activities and the name changed to IPM as a general contractor (GC). Currently, the main activities of the company are in the field of energy such as oil, gas, petrochemical, and power plant projects. IPMI now has three decades of experience, with trained, experienced experts, as well as the use of up-to-date software and hardware in all areas of project execution, as a leading Iranian contractor company with the participation of domestic partners in engineering, construction, supervision, turnkey projects, and consultancy services in major oil, gas, petrochemical, and power plant projects.

Even with the growing knowledge of project management and control in project-based companies, the existing records show the significant time and cost overruns in mega oil and gas projects in Iran. It has been reported that the majority of projects experience repeated delays due to errors and reworks (Gharaee Moghaddam 2013). Despite scientific efforts devoted to developing sophisticated project management and control methods, i.e., buffer allocation models, rare system dynamic models exist to effectively plan and control project status and replan activities and resources during the execution phase. The majority of existing project planning tools are capable of providing a new plan only by updating the activity progress manually. Hence, the management of a project during the execution phase is still mainly under the control of human experts who usually do not have accurate information about the dynamics of change-management policies and the future progress of activities. The present study was motivated by the need to develop the existing frameworks of the impact of delays and disturbance dynamics, aiming at measuring the project performance (Wynn and Clarkson 2009).

Computer simulation is one of the most widely used research methods in system engineering problems such as project management (Ilati et al. 2014). Among different simulation modeling approaches, the system dynamics (SD) approach has received growing attention due to its considerable potential to address dynamic complexities in construction projects (Gholizad et al. 2017). SD has become a widely recognized and flexible methodology for modeling and simulating the dynamic environment of projects to analyze delays and disruptions in projects. The system dynamics modeling approach is capable of analyzing the rework and error feedback loops involved in projects. Decision makers can assist the computer simulation task in predicting the future status of projects and conduct what-if tests to evaluate control strategies (Yu-Jing 2012).

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Changes are unavoidable in the project during different stages from engineering and design to implementation. Ward and Chapman (2008) indicated that the interactions between the various project components are the most significant source of changes. Providing insights into a casual relationship between the project's variables is essential to design applicable change-management policies. From a system perspective, a change in the design or engineering phase will have significant effects on the performance of the project at the implementation and construction phases. The project is like a dynamic system that is not a simple collection of system components (Cha and Kim 2018). If such a system is observed in parts, it is difficult to account for the dynamic relationships between the project components. The interaction between the project's components must be carefully addressed to handle the potential changes during the construction stage. The implication of the system dynamics tools to a complex project management is broadly acknowledged in the literature (e.g., Lyneis and Ford 2007; Tan et al. 2010). The use of SD makes new approaches available to methodically analyze the change-management system and the dynamic relationships between the project components (Demirel et al. 2017).

To fully address the main aspects of change management, integrated modeling approaches are required that provide a combined view of different factors that affect the project performance. This study aims to provide an all-inclusive view of the project change consequences, and the question of how remedial actions can affect the rate of project progress. Previous methodological efforts were frequently focused on specific project dimensions, for instance, cost or time. One of the factors exacerbated by the changes in the project is the human error and the rate of rework. If the errors are not detected by the contractor and the employer identifies them at run time, it will need to rework. However, the approval of work done in an activity means the authorization of the start of the next succeeding activities as well as the basis for paying the bills of the contractor. Therefore, the dynamic structures of error and rework have a direct impact on the cash flows of the project. In order to recognize how internal and external errors affect the entire project performance, it is essential to include not only the effects on project time, cost, resource, and quality, but also their effects on cash flows.

This article is organized as follows. The literature review is provided in the next section. The proposed methodology is described in "Research Methodology." Next, the validation process of a benchmark case study is presented in "Application of Proposed Framework." Results and related discussions are given in "Validation." Finally, in the "Conclusion" section, conclusions are drawn, and some recommendations for further researches are presented.

Literature Review

In this section, the most significant contributions in the field of project planning and control are discussed. The first effort to apply the methodology of system dynamics to project management is based on Sterman's (unpublished data, 1992) research. An early application of SD in project change management was conducted by Love et al. (2002). They proposed a modeling framework to analyze the dynamics of design errors and changes caused by unexpected events. Results of implementing the proposed system dynamics methodology in a real case study demonstrate that it can provide useful insights into how changes and their interactions influence the project performance.

Lee et al. (2006b) designed a web-based SD model for the effective management and control of errors and changes during the design process of construction projects. A collaborative system was presented to assess the negative impacts of rework cycles on project performance indicators. Motawa et al. (2007) addressed the development of a procedure for project change management through analyzing both internal and external variables. An integrated change-management system was established to simulate the dynamics of the design and construction malfunction resulting from unexpected changes and their consequences. Lyneis and Ford (2007) conducted a comprehensive survey to discuss the application of the system dynamics methodology to project management. Different aspects were addressed, including model structures, research directions, and successful implementations.

Nasirzadeh et al. (2008) considered project risk management and focused on the dynamic nature of risks during the project life cycle. An SD model was proposed to analyze risks, their interactions, and corrective actions. Due to the uncertain nature of risks, fuzzy logic was combined with the system dynamics approach. Lebcir and Choudrie (2011) analyzed the effects of project complexity elements on the project completion time through a system dynamics approach. In this context, the methodology addressed the project complexity and operations as well as their impacts on the time performance. The outcomes indicated that the project complexity was affected by different factors, including the project uncertainty, novelty, interconnectivity, and size of the project infrastructure. Boateng et al. (2012) suggested a system dynamic modeling approach to designating the effects of severe weather circumstances in construction projects. The methodology proposed provided a useful tool for planning against delays and cost overruns at the strategic level.

Although project change management is a significant area of scholarly investigation, the majority of the existing literature does not consider the integration of project dimensions into the process of formulating corrective actions. Han et al. (2013) developed a system dynamics model to analyze the dynamics of design errors and their negative effects on project performance measures. The outcomes reported indicated that design errors may delay a project, regardless of recovery actions performed by project managers. Rashedi and Hegazy (2016) developed a system dynamics model to examine the effects of various strategic policies on budgeting, infrastructure development, and the sustainability of projects. The outcomes demonstrated that the decision support framework could assess the efficiency of various project planning solutions. Grau et al. (2016) analyzed the mutual effects of the risk and change events on performance measures. The early identification of disruptive events helps to efficiently mitigate their impacts. The empirical results proved that the frequency of a disruptive event is high, and upon the increase of the frequency, the project performance will be negatively impacted. Wang et al. (2017) proposed an SD model for the purpose of monitoring and controlling projects under uncertainty. The designed system supports decision makers in preparing reactive strategies against disruptions during the project execution phase. Hui et al. (2017) provided a literature review of change dynamics in construction projects during the design processes. A conceptual framework was formulated to analyze the project management process, including performance assessment, communication, and collaboration.

As can be seen in Table 1, a taxonomy of the existing literature on project management with the SD approach is provided. Previous research has been categorized based on the focus of the research, the various dimensions of the project, and the types of change-management policies. To the best of the author's knowledge, there has been little research done in the field of integrated project planning and control under disruptive changes and reworks. Besides, despite the mentioned capabilities of the system dynamic models in dealing with complexities and the interaction among project

Table 1. Classified scheme of the existing literature on project management with SD approach

Reference	Research focus	Project dimensions: Time	Quality	Cost	Resources	Errors and reworks	Cash flow modeling	Real-world development and implementation	Change-management policies: Funding	Schedule adjustment	Outsourcing	Labor control
Love et al. (2002)	Project change management	X	—	X	X	X	—	X	—	—	—	—
Park and Peña-Mora (2003)	Project change management	X	X	X	X	X	—	X	—	—	—	X
Lee et al. (2006a)	Project planning and control	X	X	X	X	—	—	—	—	—	—	—
Peña-Mora et al. (2008)	Operational construction management	X	—	X	X	—	—	—	—	—	—	—
Han et al. (2013)	Project change management	X	X	X	—	X	—	X	—	—	—	X
White (2011)	Project control	X	—	X	—	—	—	—	—	—	—	X
Han et al. (2014)	Dynamic project management	X	—	X	X	—	—	—	—	—	—	—
Mhatre et al. (2017)	Risk assessment	X	X	X	—	—	—	X	—	—	—	—
Wang et al. (2017)	Project monitoring and control	X	—	X	—	—	—	—	X	X	—	—
Javed et al. (2018)	Productivity enhancement	—	—	—	X	—	—	—	—	—	—	—
Present study	Project change management	X	X	X	X	X	X	X	X	X	X	X

components, the practical aspects of this topic have not been addressed. Indeed, from the preceding discussion, the important research gaps are underlined as follows:

1. The necessity for an integrated method of addressing potential changes is emphasized in the literature on project management (Motawa et al. 2007), but very few studies provide solutions to achieve this goal.
2. Very few papers have considered the design of a decision support system in the process of project change management under disruptive changes and errors. The dynamics of change-management policies have not been analyzed extensively.
3. Little attention has been devoted to the incorporation of time, cost, quality, resource, scope, and performance of an integrated approach to automated project planning and control.

This study aims to present an integrated dynamic simulation approach to the project planning as well as an effective way of managing errors and changes during the implementation of that approach. Within the proposed decision support system, the project planner is capable of measuring the performance of the change-management policies.

The contributions of the present study include the following items:

1. The developed SD model presents a unified approach that addresses the process of performing the work as well as time, cost, resources, scope, income flow, and the quality that meets project goals. In fact, without the use of a comprehensive decision model, performance measures cannot be evaluated realistically. Thus, the model proposed can overcome the existing challenges by integrating the dynamics of change, error, and rework processes.
2. Significant developments have taken place over previous models, e.g., the development of a structure for the step-by-step review approval of the client based on the contents of the work.
3. Consideration of the role of the decision maker regarding the project change management in the context of the dynamic change and error structure.
4. Modeling precedence relationships between milestones and activities and the actual milestones.
5. Classification of resources in terms of the discipline and the allocation of resources concerning activities, the scheduling policy, and the criticality of operations.
6. Considering the possibility of outsourcing activities and issues concerned in the context of the provision of the contract and payment to subcontractors.

Problem Statement

The realization time of the employer's milestones is one of the effective parameters in project performance. These milestones are related to the provision of information and specifications, review, and approval of documents by the employer. Due to the fact that these milestones are the predecessors for future project activities, their delays can cause delays in the project to be exacerbated. Estimating the risk effects of these delays can provide the basis for preventive measures and increase the reliability of planning as well as the basis for negotiations between the contractor and the employer.

One of the most common responses to schedule latency is the tendency to prematurely start some activities and increase the synchronization of activities. Without proper prediction of project performance indicators, especially time and cost, these reactive actions can increase hidden errors and inevitable changes in future project activities. Therefore, modeling the effect of hidden errors on the performance indicators of the project can play an important role in controlling the project. Investigating the negative effects on the quality of activities due to scheduling pressure, including rework and error, requires the use of integrated system dynamics models. In the next section, the proposed project planning and control framework are described in detail.

In the present study, the primary research objective is to develop a comprehensive system dynamics model for the project planning and control in order to minimize the disruptive consequences of changes and errors in projects. The purpose of the simulation analysis is to decide whether the initial baseline plan can achieve its predefined goals or not. The aim is to analyze the effect of the changes requested by the employer on the robustness of the control policies. With the increase of the dynamic complexity of project management, this research would support change-management decisions and policies in ensuring the effectiveness and efficiency of the initial project plan. It is expected that the outcomes of this research will further extend the application of simulation modeling frameworks to project and control processes.

Research Methodology

This section provides a dynamic simulation approach that enables the decision maker to model nonlinear relationships that are inherently complex, dynamic, and involve multiple cause-and-effect feedback loops. A summary of the inputs and outputs of the system dynamic model is depicted in Table 2. Using Vensim Professional as the core programming engine, the model supports decision makers by simulating and evaluating remedial actions. One of the important features that enable the model integration is Vensim's subscription language capability. This feature supports creation of advanced arrayed models. In this way, structure creation, repeating, and debugging are more straightforward. Once a subscript is added to the original structure, the numerical values for all structures can easily be adjusted. Besides the simulation engine, Microsoft Excel provides a platform for data input entry. It can preprocess data collected by users, transferring them to CSV format for Vensim. Also, Vensim generates report worksheets in Excel. For ease of use, a sensitivity analysis panel has been designed. In this panel, the user can change the input variables, i.e., the hire time, the maximum workday, and the minimum attractive rate of return (MARR), to evaluate the results of performance measures, e.g., the project progress and the income cost.

The present project change-management model is based on the extension and integration of the valid causal feedback loops available in the literature and the data obtained from the case study and the project management training workshops. The system dynamics–based project modeling approach has been successfully applied to deal with the dynamic complexities of projects. System dynamics use rigorous theoretical foundations within a holistic approach to model a dynamic system (Han et al. 2014). In the next part, the significant elements of the system dynamics model developed for practical project change management are discussed. The system dynamics methodology is illustrated in Fig. 1. The model inputs include the list of project activities and their associated information (project network, precedence relationships, and time and resource requirements), the actual progress of activities, the number of resource disciplines, the maximum availability of resources, and the cost of hiring resources. The system outputs include qualitative indicators, i.e., work progress diagrams, Gantt chart, resource profile diagrams, the probability of the on-time project completion, budget revenues, and the project cost progress.

Model Scope

As previously mentioned, this article tries to develop an integrated simulation model that can simultaneously handle the project complexity and its dynamics in the case of delays and disturbances. Endogenous variables are a measure of operational parameters of the project. Exogenous variables in the model are stable, and there is no feedback on them within a project. The selection of the variables is mainly based on the conditions significantly affected by the real-world project studied. The model aggregation level shows the detail and variety of the key elements used in the model. An important assumption regarding the aggregation level is the definition of the main material flows during the project. In this model, a primary work unit (WU) is defined for the accurate integration of the model's structures. Depending on its size, each activity has been formed of a number of work units. Since the model has been developed for an engineering project, it is assumed that there are only human resources in the project. Activities are performed in different sectors of specialties or disciplines. Moreover, it is assumed that each discipline has certain resources that are all of a single type.

Model Structures and Feedback Loops

In terms of the internal structure, an SD model is a set of differential equations. These equations allow for the simulation of a large number of activities, communications, and processes. In this study, Vensim Professional software was used because it is capable of modeling the activities, time, resources, and policies through

Table 2. Inputs and outputs of the system dynamics model

Category	Input items	Output items
Activity and milestones information	Planned durations	Activity start and finish times
	Precedence relationships	Reliability and actual stability
	Reliability and stability	Rate of rework
	Accuracy of scope and quality management	Overtime work
	Internal and external sensitivity	Quality index
	Number of required resources	Real labor productivity
Overall project information	Project planned duration	Project completion time
	Contract cost	Project's progress over time
	Cost of staff salaries	Net present value of cash flows
	Total number of disciplines	Resource usage curve
	MARR	Work-hours of project
	Overtime	Number of outsourced activities
	Hiring	Rework ratio
	Outsourcing	Project quality index

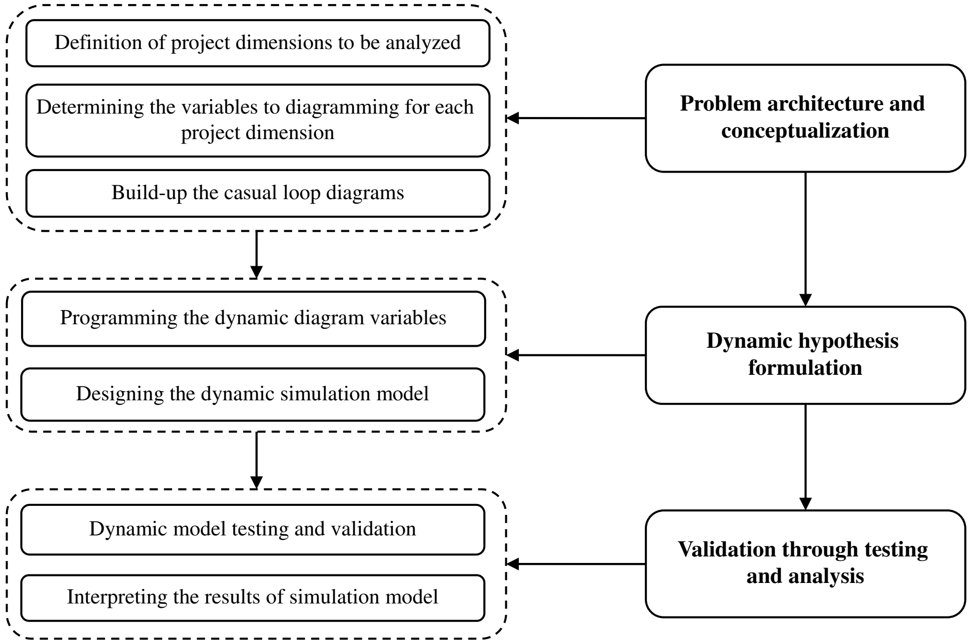

Fig. 1. Architecture of the developed system dynamics model.

spreadsheet formats, and also implementing and evaluating simulation model output graphs, tables, and Gantt charts as well as project performance in order to achieve the objectives. The structure of the model is discussed in the following sections. During the development of the simulation model, in addition to the adaptation of existing models in the literature, the conditions of the case study are also significantly taken into account.

Subsystems

The model presented in this study is divided into five subsystems, including the scope and performance of work, project progress, changes and errors, resources, and project performance. Fig. 2 demonstrates the content of the different subsystems of the developed simulation model and the interactions among them. Some of these subsystems are also broken into several parts. These subsystems and components are linked through common variables.

The model feedback loop structures and the method of their adoption from the literature are summarized in Table 3. In each part of the simulation model, the structure of the model has been developed based on the extension of the existing casual loop or the field study. The model subcomponents are discussed in the following sections.

Structure of the Scope and Performance of Work

The dynamic structure of the work includes elements representing the completion stages of the activities. The workflow is added to the stock variable called ready to work, with respect to the precedence relationships among activities and the availability of human resources. Afterward, the work is performed at a definite rate, and it is added to the stock variable called quality control. If no error is discovered, work units ignore this stock variable and go through the work under client approval stock variable. Otherwise, if an error was detected in the aforementioned work unit, it would be sent back to the stock variable called ready to work.

If errors are not detected by the contractor and instead the client identifies them during the revision process of the work performed, the part of the work with problems will be sent back to the contractor because of the rate of rework on the performed work. If the work performed does not have any defects from the client's point of view, it will be accepted and transferred to the approved work stock variable. The approval of the work conducted is tantamount to permission to start the next dependent activities, and also it is considered as the basis for payments to the contractor. However, there is the possibility that a part of an approved work needs rework due to the changes or errors identified later. This condition has been modeled by defining the rate of rework on the approved work. This variable returns the work units within the approved work stock variable to the category of work ready. Fig. 3 illustrates the flowchart of the structure and performance of the work, as well as covariates.

Due to the abundant number of activities in project models, the index control module of the Vensim software that enables researchers to define the activity-related variables and to have them indexed has been used. These activity-related indexes are defined as the activity codes of the project. The range of an activity is a function of its main duration. The mean duration of the operation, which can be assumed as its optimistic duration, equals the duration of performing the main work regardless of the time elapsed between sending the report of the work performed and receiving the revisions. It is calculated based on the assumption that no error has been detected or no change has been made to the activity and that all resources and information required are available. In this model, instead of entering the time of the activities planned, called original duration in project management software such as Primavera, first the main duration of the activity is entered as the basis for estimating the activity scope. Next, regarding stages such as quality control, revision, and approval by the client as well as changes made or errors, the model calculates the final duration. In order to establish a relationship between the volume of the work and the work units, as proposed by Lee (2006), it is assumed that every working day (an average of 8 h per day) is equivalent to 1,000 work units. Therefore, the volume of the activity is obtained by multiplying the mean duration of the relevant conversion variable.

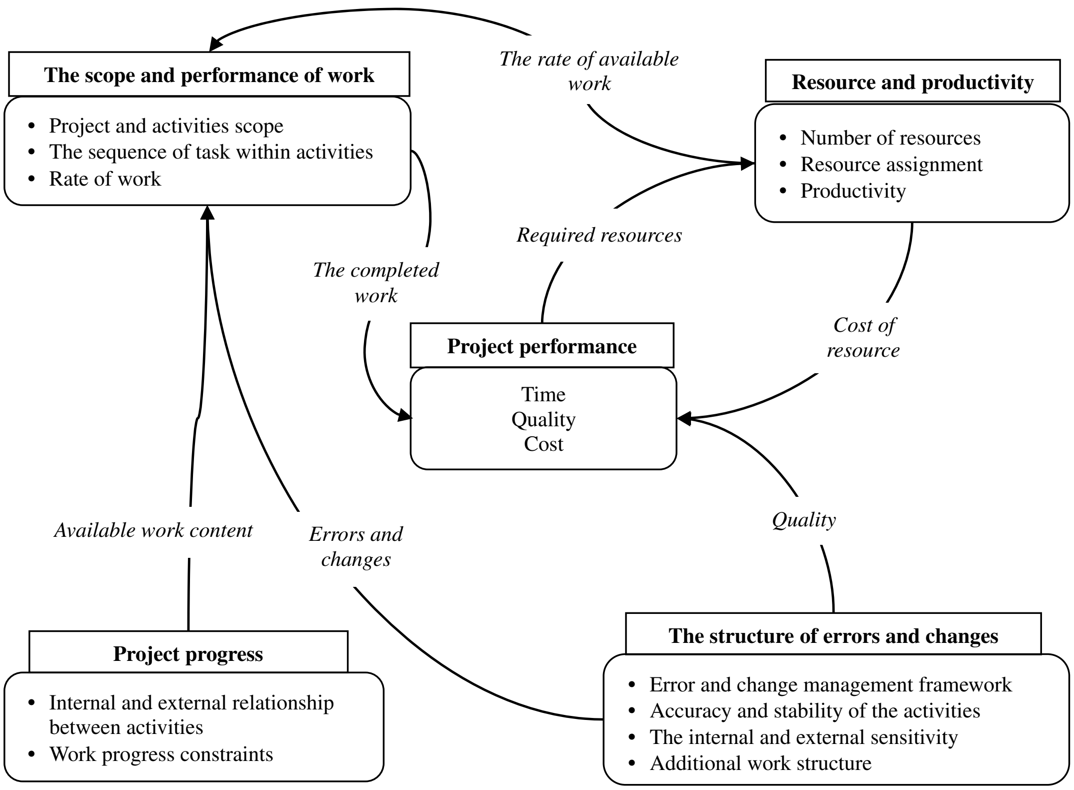

Fig. 2. Subcomponents of the integrated system dynamics model.

Table 3. Model structures adopted from the literature

Model structure	Source of implementation
	Scope and work
Structure of available work	Lee (2006) and field study
Process and resource-based constraints on the work rate	Ford (1995), Ford et al. (2007), Park (2005), and field study
Structure of duplicated errors	Lee (2006)
	Project progress
Calculate and project progress activities	Field study
Internal precedence relationship	Lee (2006)
External precedence relationship	Sabzehparvar and Seyed-Hosseini (2008), Lee (2006), and field study
	Changes and errors
Structure of changes and errors	Lee (2006)
Structure of rework and additional work	Lee (2006), Rodrigues and Williams (1998), and field study
Structure of parallel flow for changes and errors	Lee (2006) and Park (2001)
Structure of changes requested by the employer	Field study
	Resources and efficiency
Structure and regulation of resource allocation	Field study and Ford et al. (2007)
Rate structure and resources required	Field study, Ford et al. (2007), and Park (2005)
Overtime structure	Field study, Ford et al. (2007), and Park (2005)
Productivity structure	MacInnis (2004), Ford et al. (2007), Park (2005), Lee (2006), Flynn (2007), and field study
Outsourcing structure	Field study
Structure of employment of resources	Field study
Structure of leave personnel	MacInnis (2004) and field study
	Project performance
Structure of timing pressure	MacInnis (2004) and field study
Structure of anticipated completion time	MacInnis (2004) and field study
Structure of completion time	Sabzehparvar and Seyed-Hosseini (2008) and field study
Structure of revenues and net present value	Field study
Cost structures	Field study
Structure of the project budget	Field study
Quality structure	Ford (1995), Lee (2006), and Rodrigues and Williams (1998)

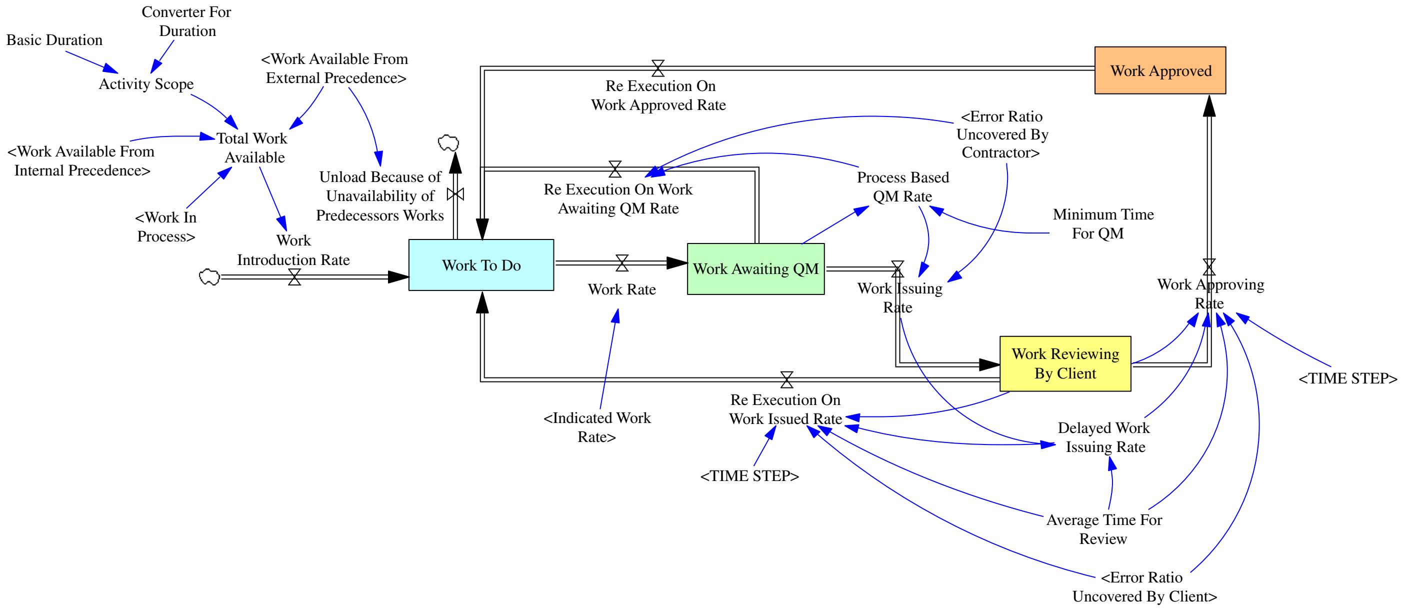

Fig. 3. Structure and process flowchart of the implementation work and scope.

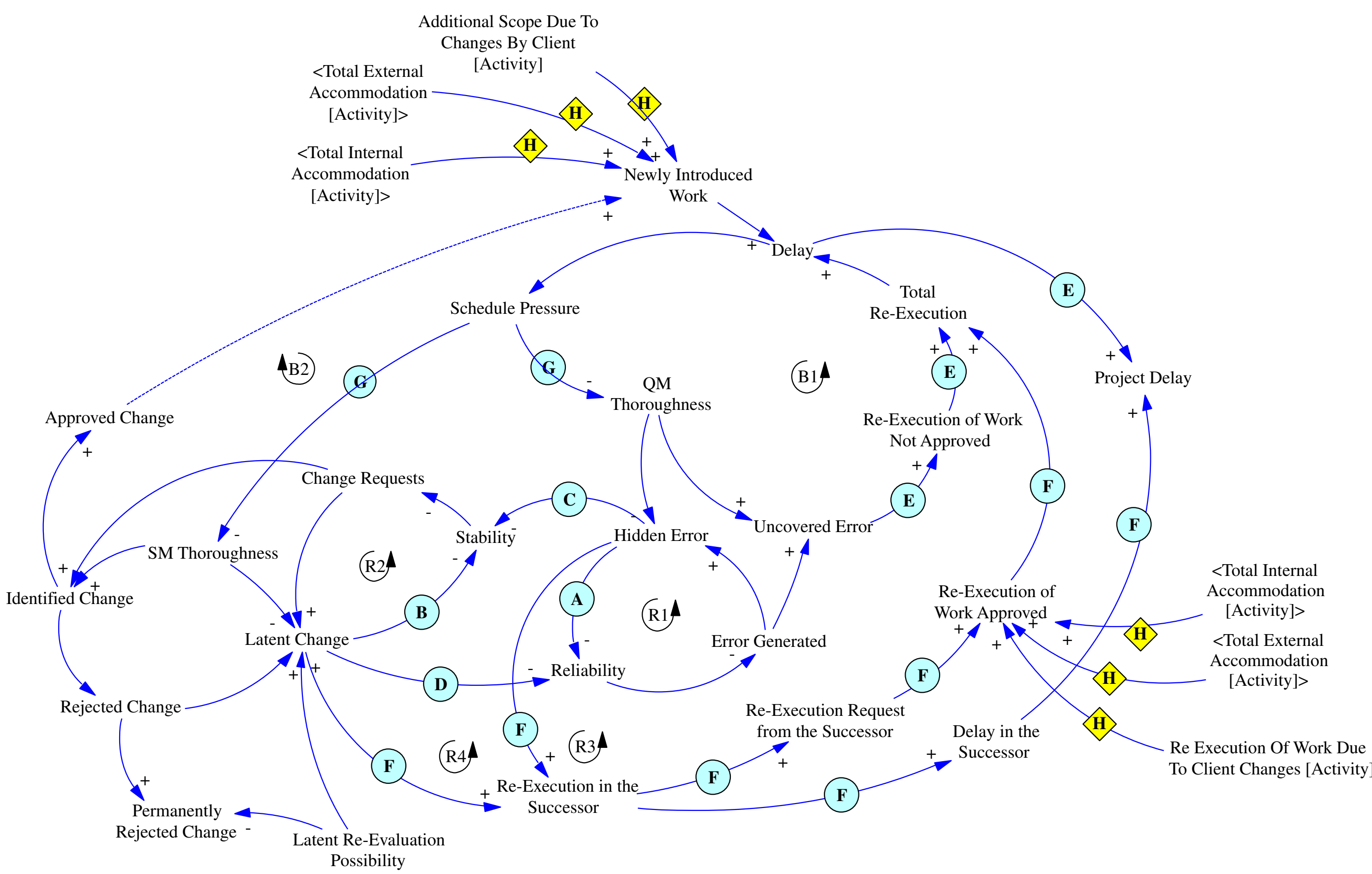

Fig. 4. Cause-and-effect diagram for errors and change management.

Causal Loops for Errors and Change Dynamics

According to the framework described for changes and errors, a causal diagram that represents feedback processes generated by errors and changes is demonstrated in Fig. 4. Link A shows that the hidden errors (of previous activities) may decrease the reliability of the following activities that create the amplified Loop R_1. Link B shows that the hidden changes can also reduce the stability of activities. The hidden errors may cause damages to the stability of an activity, which would result in changes to the activity (Link C in Fig. 4). This situation can be developed to cover changes (Link D in Fig. 4). In addition, the scope has been adjusted and if it is not adjusted, it will ultimately lead to delays. In order to improve the decision-making process, delays caused by downstream activities of Link F have emerged as hidden errors, and latent changes are instantly recognized. Cumulative delays and the schedule pressure may degrade the performance management processes, quality management, and scope (Link G). If the pressure schedule reduces the accuracy and quality management processes of the management due to delays, there will be less need to apply a revision to the process of the discovery of errors, and consequently there will be less need to conduct any extra work due to such errors. As a result, the activities are carried out more quickly (Loops B_1 and B_2).

Causal Structure of the Budget and the Cost

In this section, the budget structure, costs, and revenues of the project will be investigated. Project costs include direct and indirect costs. In engineering projects, direct costs include the salaries of the personnel of various disciplines and fees paid to subcontractors (outsourcing). Indirect costs are overhead costs not spent directly on the product development project, but which are necessary for the progress of the project. The required work rate is determined based on the remaining time and the amount of the work. Next, the effective workforce required will be determined based on the rate of the work needed that could be provided through overtime, resource allocation discipline, recruitment, and outsourcing. By increasing the effective labor force, the work rate will increase, and consequently there will be an increase in the amount of the work completed, reducing the work remaining as well as the need for more resources (Loop B_1).

The project resource cost increases upon the growth of resource usage. These costs consist of regular payment and overtime, personnel, overhead costs (as a coefficient of direct costs and staff salaries), and the costs of outsourcing contracts. The costs constitute the total costs that must be paid. Paying the costs decreases payable costs (Loop B_2), yet it simultaneously leads to the consumption of the project budget. If the proportion of the funds to the amount of payable fees is not high, a budget deficit occurs that will lead to cost limits. The inability to pay the costs results in different reactions throughout the system. One of the most common reactions in the case of budget deficits is the delayed payment of the project team. Delayed payments reduce costs and the consumption of the budget, so the budget deficit will be prevented (Loop B_3). However, delays in the payment of staff salaries also have negative consequences such as a lack of motivation. This factor increases staff turnover and reduces productivity, and it consequently decreases effective resources and the work rate. By reducing effective resources and labor rates, the completion of the work will happen at a slower rate. The work done by a contractor is the source of the project income that is paid on behalf of the client. Therefore, the reduction of the labor rate and consequently the completed work causes a decrease in the project income that ultimately intensifies the shortage of the project budget (Loop R_1). However, by the completion of current activities, when the corresponding income is paid by the client to the contractor, the budget deficit will be solved and the costs will be payable in arrears. Moreover, in the case of a severe budget deficit, the payment of subcontractor costs may be postponed (Loop B_4). This condition will ultimately lead to stoppage of the work by the subcontractors, which reduces the speed of the work completed and lowers the project income (Loop R_2). Another common reaction to the lack of funding is the increase of efforts to accelerate the work to complete more work, and as a result receive more money from the client. If a strong relationship exists between the duration of the project and project costs, accelerating the work progress to complete projects faster reduces the total costs of the project. This effect is shown in balancing loop B_4 (Fig. 5). The constant scheduling pressure decreases staff morale as well as productivity. By the reduction of the workforce turnover rate, the effective workforce performance rate and the work rate decrease. By reducing the effective resources and labor rates, the work will be done at a slower rate, and the achievement speed of incomes increases and this intensifies the

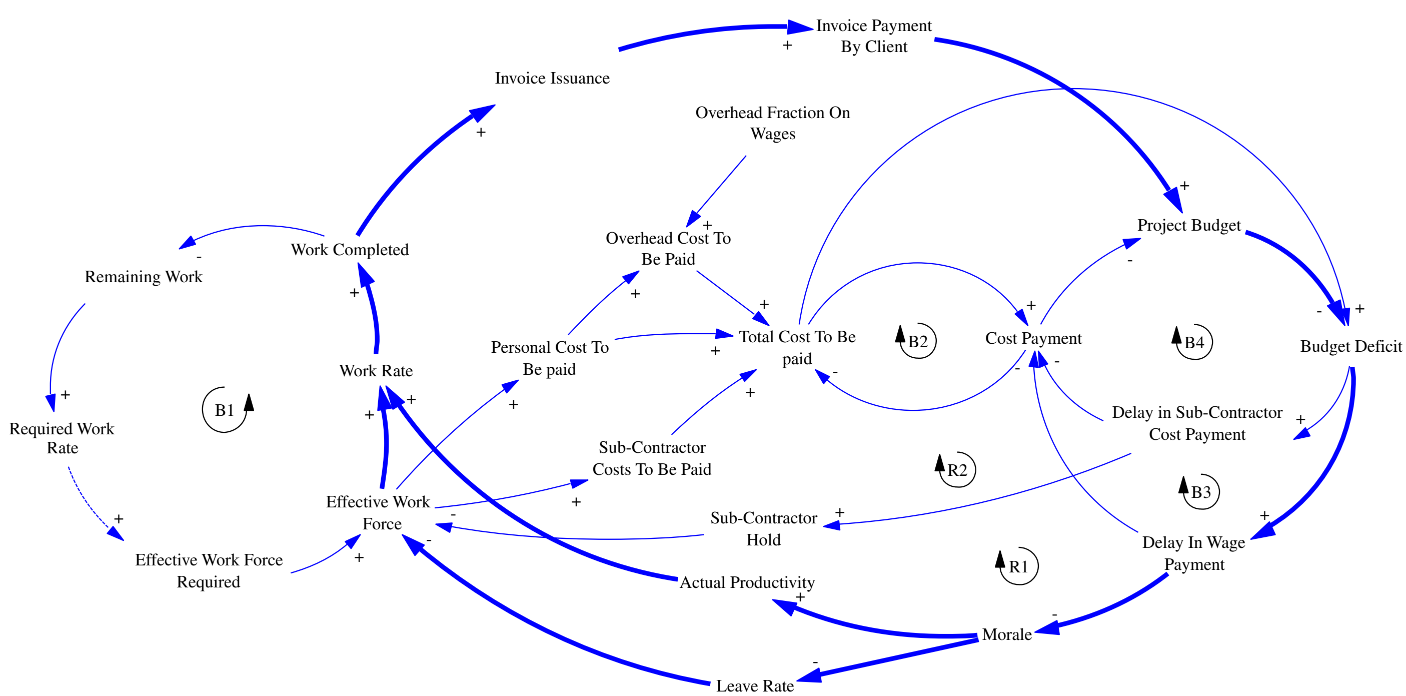

Fig. 5. Simulated versus planned project progress (reliability and robustness = 0).

Table 4. Work discipline and their codes

Work discipline	Code
Structure and building	BU and ST
Electrical and telecommunications	EL and TL
Control and instrumentation	IN
Piping and modeling	PM
Rotary	MA
Static equipment	ME
Civil	CV
Safety	SF
Process	PR
Painting	PT

Table 6. Results of the project in case of changes and adopting outsourcing policy (MARR = 0.25)

Project performance indicator	Value
Project duration (days)	852
Project cost at completion (million dollars)	6,260
NPV of cash flows (million dollars)	1,085
NPV at the end of the project (million dollars)	0.753
Outsourcing (%)	20
Quality measure of project (%)	99.76
Rework (%)	29.52
Errors (%)	23.7%
Cumulative project work-hours	307,000

budget deficit (Loop R_3 on the appropriate links have also been added).

Application of Proposed Framework

This section investigates the policies to improve the completion of a specific project described using the proposed SD model. First, a brief description of the real-world project will be presented. Next, the data collection and validation tests will be discussed. Finally, the performance of the project will be predicted through simulation results, and the change-management policies will be tested. The case study includes detailed design phases of the South Pars project under the supervision of IPMI. The project is located at the site for Phases 17 and 18 in Asaluyeh, Iran. The project scope includes the detailed engineering and procurement services for utility units. The project consists of 180 activities, 10 work disciplines, and 48 milestones. Table 4 provides the work disciplines and their codes defined in the project design plan.

Project deliveries include the daily production of 50 million cubic meters of natural gas, 80 thousand barrels of gas condensates, 400 tons of sulfur, and an annual production of 1 million tons of ethane and 1.05 million tons of liquefied petroleum gas (propane and butane). It is estimated that the project will be completed within 25 months on the contract budget of $8,003,600.

Recorded Changes in the Project

In the first contract, the key milestone contained important characteristics of the project, and it is the prerequisite for 46 project activities that was not fully confirmed by the client. Five months after the start of the project on March 12, 2008, the company requested resubmission of all documents, based on recent comments made on the changes. The project performance was simulated in the normal mode and the occurrence of changes. To simulate the effects of changes on the project performance, simulations will be made in the absence of changes. Prior to simulating the model, a number of important assumptions were made about the difference between the normal mode and when the changes are applied to the project conditions (Table 5). The objective of the simulation analysis is to decide whether the initial baseline plan can achieve its predefined goals or not.

The results of the project simulation in the case of the change occurrence and using the outsourcing policy are given in Table 6. The result includes the project completion time, cost, and cash flow. As a measure of the profitability of a project, net present value (NPV) was used in analyzing the change-management policies. A standard way of calculating the project's NPV is proposed in Eq. (1)

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{\mathrm{NCF}(t)}{(1+r)^t} = \sum_{t=1}^{T} \frac{I(t) - C(t)}{(1+r)^t} \tag{1}$$

where $\mathrm{NPV}_{(t)}$ = net present value in year t; $\mathrm{NCF}(t)$ = net cash flow in year t; $I(t)$ = project income for the year t; $C(t)$ = project cost in year t; r = discount rate; and T = project life cycle.

Recruitment was completed based on the main plan. The maximum amount of overtime was 12 h. The outsourcing policy was applied to up to 25% of the activities of each discipline. As the outcomes show, the occurrence of changes, using the current human resources for the project, leads to a 220-day delay in the completion time of the project. Therefore, the simulation was repeated assuming that the outsourcing policy is used to prevent the degradation of the performance of the project.

Performance Assessment of Change-Management Policies

The most common reactions to the changes in the project were to claim compensation in the form of extending the time of the project or increasing the amount of the contract cost. In this context, the project management team offered two proposals to the client:

1. The extension of the project from 25 to 31 months, without increasing the contract cost; and
2. The extra payment of $350,000 from the company and the completion of the project in accordance with the main program in 25 months.

IPMI also proposed that the client company would accelerate the process of the project review and the approval process of

Table 5. Parameters and assumptions related to the normal scenario and the changes mode

Model parameters	Normal mode (without changes)	With changes
Milestone characteristics	It is completed from the beginning of the project	The specifications of this milestone are not completely clear from the beginning. As the characteristics of the process activities change after 5 months from the start of the project, it will gradually be determined by the 9th month
Stoppage or re-enforcement of activities	—	Process activities are executed again
Average time for review and approval of the employer	Based on the contract (15 days)	25 days

Table 7. Results of the simulation model under different scenarios

Project performance indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Project duration (days)	850	836	773	751	937	945
Project cost at completion (million dollars)	6.128	5,993	5,754	5,530	6.566	6.679
NPV of cash flows (million dollars)	1.446	1,564	1,864	2,043	1.093	1.012
NPV at the end of the project (million dollars)	1.022	1,146	1,489	1,637	0.736	0.674
Outsourcing (%)	19.44	19.44	19.44	16.66	11.11	0
Quality measure of project (%)	99.74	99.75	99.75	99.75	99.73	99.72
Rework (%)	28.47	28.23	27.26	27.02	24.77	24.58
Errors (%)	22.72	22.50	21.53	21.04	19.18	19.24
Cumulative project work-hours	303,000	300,000	289,000	286,000	289,000	285,000
Human resources recruitment plan	AP	AP	New plan	AP	AP	New plan
Maximum overtime (h)	12	12	12	12	12	12
Outsourcing policy in each discipline	Up to 25%	Up to 25%	Up to 25% + 11 selected activities	Up to 25% + 11 selected activities	Up to 25%	—
Project time extension	—	—	—	—	X	—
Schedule adjustment	—	—	—	—	X	X
Resource allocation policy	AP	M	M	M	AP	M
Average employer review time (days)	AP	AP	AP	15	AP	AP

Note: AP = as planned; and M = maximum resource allocation for a number of activities.

documents more quickly and efficiently. The maximum amount of overtime is 12 h. The outsourcing policy was applied to up to 25% of the activities of each discipline. The payment of $350,000 by the client was assumed in the 12th month. Table 7 provides the simulation results of the changes to the project when the contract cost increases.

Considering the identified important critical paths in this project, through the maximum allocation of applicable resources to these activities from the beginning to the end of the path or outsourcing other activities, an improvement can be made during the project completion time. The planned outsourcing and the recruiting of more people in a number of disciplines can reduce the length of critical paths. As is observed, the actual time of the project completion takes 90 days over the time planned. Therefore, one should adopt some policies to reduce the length of critical paths. One of these policies is the increase of the resources to expedite the progress of activities. Considering the important critical paths identified in this project, through the maximum allocation of the applicable resources to these activities from the beginning to the end of the path or outsourcing other activities, an improvement can be made during the project progress.

The results of the project simulation for different scenarios are shown in Table 7. In some scenarios (1, 2, 4, and 5), it was assumed that recruitment occurred according to the initial plan. The maximum amount of overtime was 12 h. The outsourcing policy was applied to up to 25% of the activities of each discipline. The payment of $350,000 was confirmed by the client in the 12th month. According to the results of the first two scenarios, the maximum allocation of the resources to the key activities from the beginning of the critical paths reduced the completion time of the project by 14 days. If it is possible to outsource a number of process activities based on a predetermined plan and also recruit more people to provide more resources to this discipline, it will be possible to start the important process activities in this path earlier. Along with this critical path, there is an activity in the electronic discipline and five activities in the civil discipline for which resource constraints have led to a delay at the beginning or to a slower progress. Therefore, preplanned outsourcing as well as recruiting more people in these disciplines can help shorten the length of this critical path, being a process discipline itself. The analysis of the other critical paths signifies the shortage of resources in the disciplines of precision instruments and safety.

In Scenario 3, it was assumed that the recruitment occurred according to the main plan. The maximum amount of overtime was 12 h. In addition, the outsourcing policy was applied to up to 25% of the activities of each discipline. The payment of $350,000 by the client in the 12th month was confirmed. The fourth scenario was conducted on the assumption that after the 12th month, the response time of the client is reduced to 15 days, according to the contract. This scenario shows the results of the project simulation in the case of increasing the contract cost, with the new settings in the resource plan and a reduction in the response time of the client. As is observed, the reduction in the revision and response time by the client to 15 days has an intensely positive impact on the reduction of the completion time of the project. However, in the case of extending the project contract, it was assumed that the recruitment took place according to the initial plan. In Scenario 5, the project duration could be extended up to 940 days. As is demonstrated, by the extension of the project time, the project can be completed within the determined time. However, compared with adopting the policy of increasing the contract costs, the time extension policy has more costs. Adjustments to the resource-allocation program, especially given the critical paths, can be made based on the outsourcing policy renewal time without the use of the finished project. In the last scenario, project extension was allowed without permission for outsourcing. The recruitment was performed according to the initial plan and the maximum amount of overtime was 12 h. As can be seen, this policy resulted in higher project cost at completion; on the other hand, the rework rate was minimized.

In the last case, paying more attention to the critical path activities and exerting more control over them are essential. It is also necessary to use the maximum level of resources to expedite such activities. The simulation results are shown in Fig. 17. Similar to the policy of increasing the cost of the contract, reducing the response time of the submitted documents by the client has a positive effect on the performance of the project period, so the project completion time will decrease from 945 to 921 days. Table 8 gives the summarized results of the comparison made among change-management policies in the project under study.

It was observed that when no control measure was adopted by the project manager, the risk analysis results were not realistic. In this case, major changes will be observed through modeling such measures. The analysis must consider the direct and side effects of such control measures thoroughly.

Table 8. Summary of the results of policies and comparing with a basic scenario

Scenario	Project duration (days)	Project cost at completion (million dollars)	NPV of cash flows (million dollars)	Outsourcing (%)
Without change	753	5.015	2.458	0
Increasing cost (with changes)	773	5.754	1.864	19.44
Project extension without outsourcing (with changes)	945	6.679	1.012	0

Validation

In this section, using the simulation model outputs, the project behavior is analyzed in terms of changes in three dimensions of time, cost, and quality. Validation is the process of creating confidence in the meaningfulness and usefulness of the model (Sterman 2000). Validation is a continuous process model, and the present model has been validated from the beginning of development to completion in various aspects. Therefore, the following explanations include the description of the validation of the model in the middle stages and in the final stages. The main source for validation techniques was adopted from Sterman (2000) and Richardson and Pugh (1997). Barlas (1996) categorized the validity tests into behavior validity and structure validity. In this study, we aim to address both aspects of the model validity.

Model Boundary Test

The boundary condition test examines the suitability of the boundary of the model for the desired purpose. The first step in this test is to determine the boundary of the model. As previously explained, the extraneous and excluded variables are completely separated from each other. Regarding the principle that the exogenous variables used in the model (constant values) can behave as variables and change over time, there were some investigations for feedback from inside the model. For example, the tendency to change scheduling variable, which appeared in the structure of the project planning, was first modeled as an exogenous variable. But with interviews with IPMI's project control experts, this variable was considered as a function of the predicted latency at the completion of the activities. Some of the exogenous variables, such as the progress of the project plan, the completion time of the project, and the contract cost of the project, will necessarily require a review due to major changes. But since the value of these variables is determined by negotiation between the employer and the contractor, it is not logical to model these variables as endogenous.

Another important issue in the model boundary test is to ensure that important feedback loops are involved in the model. In the present case study, by interviewing the project team members and reviewing the literature, the main feedback loops were determined for the purpose of the model. Some of the feedback structures in the previous research, due to the lack of application in the study project, were eliminated from the structure of the present model. For example, the effect of experience of human resources on the reliability and sustainability of activities (Lee et al. 2006a), which itself involves modeling the structure of experience and personal learning and feedback from the structure of work progress and resources, has been neglected. This is mainly because of the fact that the nature of the project under study has repetitive activities and IPMI personnel have a high level of experience.

Structured Verification Test

The purpose of the verification test is to determine if the structure of the model matches the actual knowledge of the system. This test is based on conforming to the model with the main physical realities, such as the law of survival and realism in the decision-making rules of the system's agents. As previously mentioned, the model was developed to a detailed level of activities to take into account the interactions and connections between activities from important perspectives such as variations and errors.

The law of the survival of the substance has been specially considered in the structure of the scope and execution of the work. Due to the fact that during the implementation of the project some additional work is due to internal and external errors and changes, it must be ensured that eventually the amount of work approved for each activity is equal to the initial amount plus all the additional work that has been created. Investigating the values after the simulation has shown the establishment of this relationship. Another example is the adaptation of the structure of the model to physical reality by the prevention of irrational values, such as negative values for parameters such as work ready to do, human resources activities, and budget, which proper formulation of this phenomenon resolved.

The structure of decision rules is in accordance with the decision-making process of the planners and the project manager. The desired status and expected status of the variables are distinguished from one another, and physical constraints have been accounted for to achieve desired results. For example, the expected levels of resources required for activities with the actual amount of resource allocation (due to the limited resources available) are distinguished from each other. Under certain conditions, the decision rules must have the necessary solidarity. These rules should produce outputs that are physically feasible and operational in terms of meaning. For example, the rates of payment from the project budget are adjusted in such a way that it does not result in a negative budget.

Dimensional Compatibility Test

This test involves analyzing the dimensional compatibility of the equations. During the development of the equations and variables of the model, their reputation was also determined and tested automatically by the software. In the proposed model, all equations are dimensionally compatible without introducing additional factors that do not have a corresponding concept in the real system.

Boundary Condition Test

Under extreme conditions, equilibrium means that the model should be realistic, even with inputs that are infinitely or very small. For example, if the amount of resources reaches zero, the rate of performance should be stopped because work cannot be done without resources. Boundary condition test can be done in two ways: (1) by direct examination of the equations of the model, and (2) by simulation. In the first method, the decision-making equations are tested to determine if the output of the decision is feasible and reasonable for inputs with the maximum and minimum values. This test should also be conducted on management policies. In the proposed model, a variety of boundary conditions were applied to the model, which is typically referred to as reliability and stability tests.

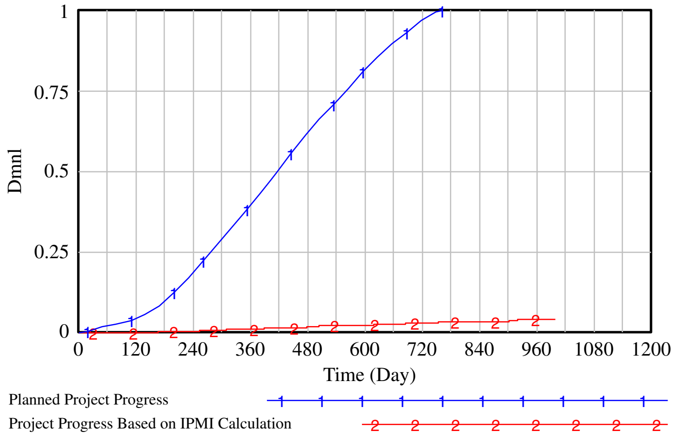

Fig. 6. Project progress graphs in the case of zero-level resources.

One way of testing a model is to change the reliability and achieve the lowest possible degree of stability of the activities. In this scenario, given the fact that the whole work requires change, the accepted work rate should be zero. But this is where the quality and scope management of the project is 100% accurate. Since the accuracy of quality and scope management is not 100%, a small amount of progress will be observed (Fig. 6).

Another boundary condition test is the reduction of the resource level of the project to zero. In this case, the amount of active and pending resources in each discipline is zero and the recruitment schedule is also eliminated. Fig. 7 shows the project progress curve in this case. As shown in this figure, the project, despite the lack of resources in the organization, progresses to a certain extent, and after a while the project's progress is stopped. This kind of behavior of project progress is due to the use of outsourcing policies for activities that stop after reaching the specified limit (25% of the total activities in each discipline).

Completion Time Analysis

As the results of the previous section indicate, the project completion time increases from 760 to 852 days due to client-requested changes. In general, the completion time of a project is influenced by the critical paths in the network of activities. In case of changes in the scope of the project, a critical chain of activities in the project is formed as depicted in Fig. 8. In the modeling framework, the Gantt chart is used as one of the default software tools for the Vensim Professional software. Fig. 9 shows the critical chain of the project as a Gantt chart. In this figure, the upper bar represents the start and end of the simulated activity, the middle bar shows the resource allocation interval, and the lower bar indicates the planned activity interval. For example, A_{43} is a process activity that, given the precedence relationships, can start from day 91, but its delay is due to accumulation of process activities, their uncertainty, and lack of resources. As mentioned previously, until the 11th month of the project, the outsourcing policy has not been used, but the use of outsourcing can be considered as one of the decisions to expedite work when resources are scarce. It is assumed that after 12 months, the outsourcing policy is allowed for some process activities. As such, the A_{43} activity is outsourced and will begin on the 396th day of the project and after setting the contract with the subcontractor.

Fig. 10 shows the resource profiles for process discipline under different policies. The resource profiles include (1) available resources in the discipline, (2) resources provided by outsourcing, and (3) the amount of resources required for the process discipline. As shown in this figure, on the 250th day, 20 process activities that have been scheduled to begin before 120 days become ready for execution. Also, Fig. 11 shows the resource profiles for the civil discipline under different policies. The number of current personnel in the discipline process is nine people. Due to the reimplementation of the process activities and the gradual confirmation of the key milestone specifications, more resources are needed to complete the activities as planned. In this case, a number of process discipline activities, including A_{43}, are outsourced.

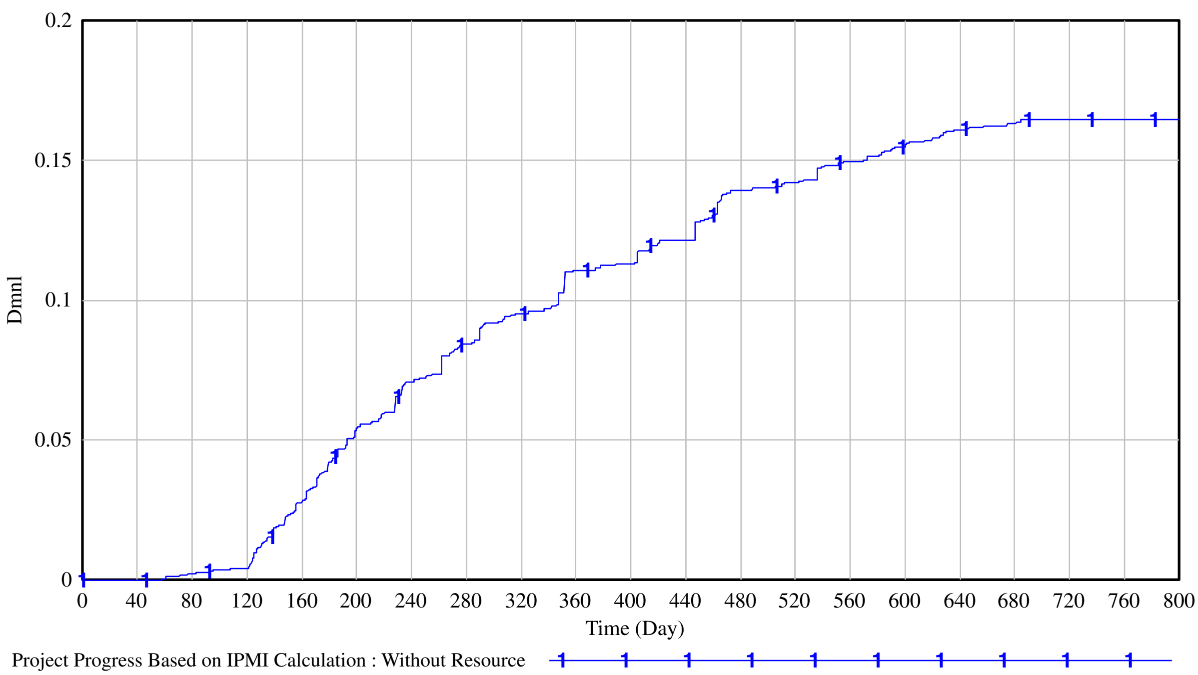

Fig. 7. Causal diagram of the budgets and costs.

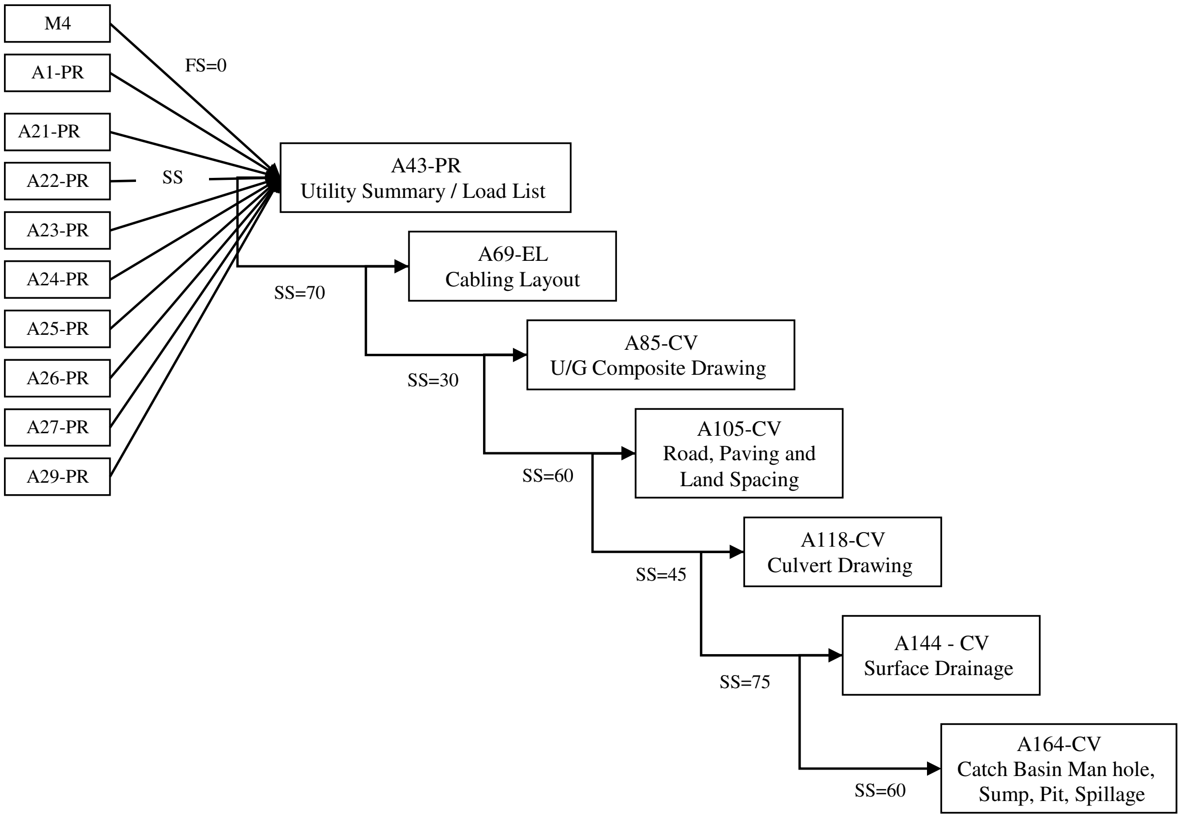

Fig. 8. Longest critical chain of the project (with change).

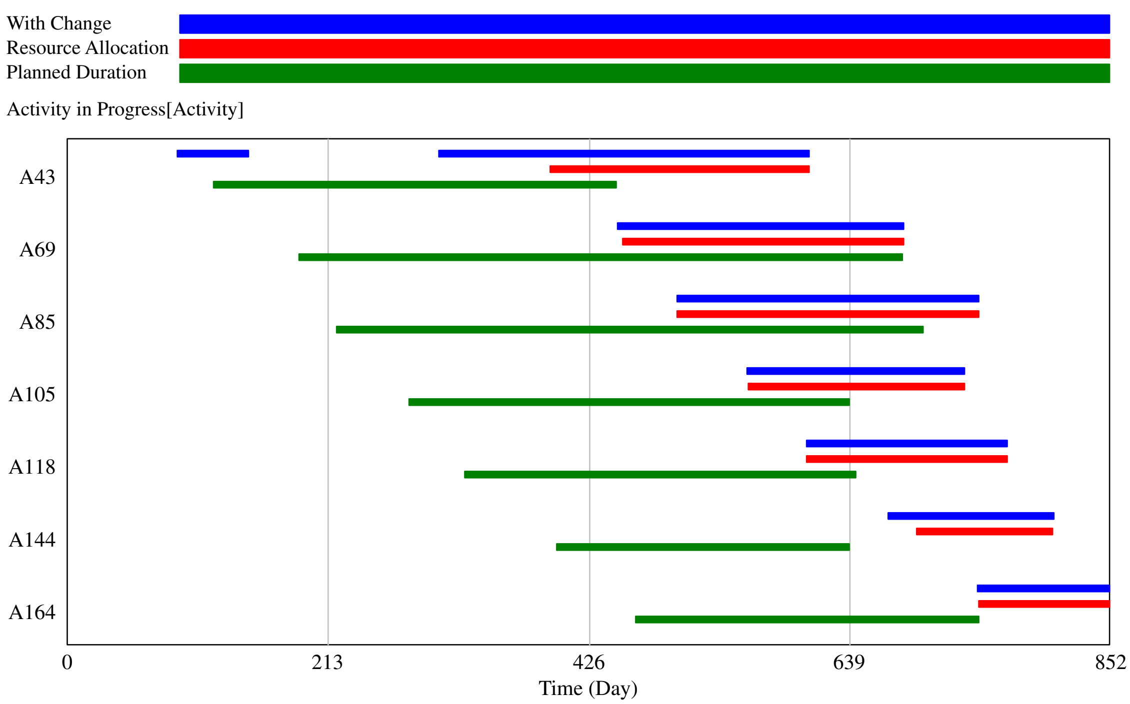

Fig. 9. Gantt chart of the schedule and critical path (between activities A_{43} and A_{164}).

If no changes are requested from the employer, activity A_{43} ends with a normal number of resources in 240 days. However, if the employer requests changes, despite the use of the maximum number of resources (twice the normal number), the speed of progress of this activity is not expected and this activity will end at 217 days. This is due to the high rate of rework in this activity. Fig. 12 shows the rate of duplication of work under quality control in both the state of change and the change for activity A_{43}.

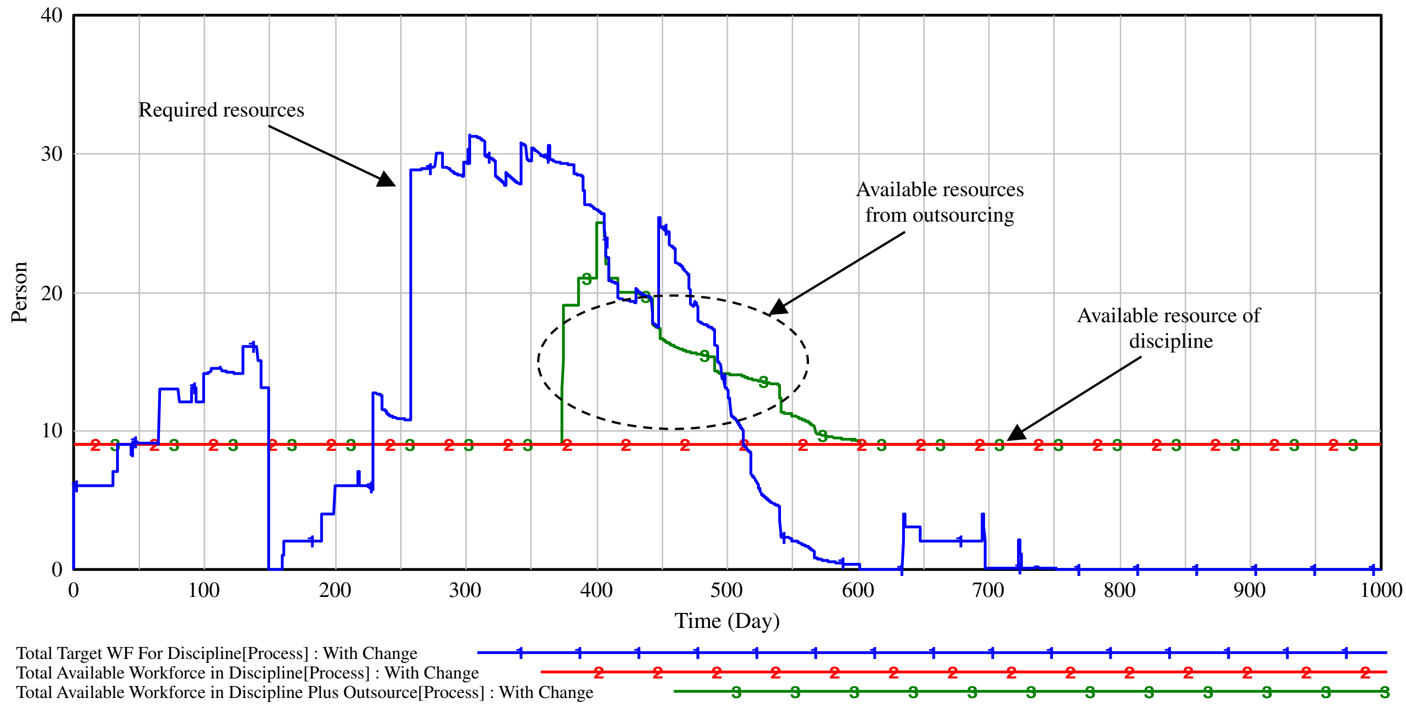

Fig. 10. Resource profiles for process discipline under different policies.

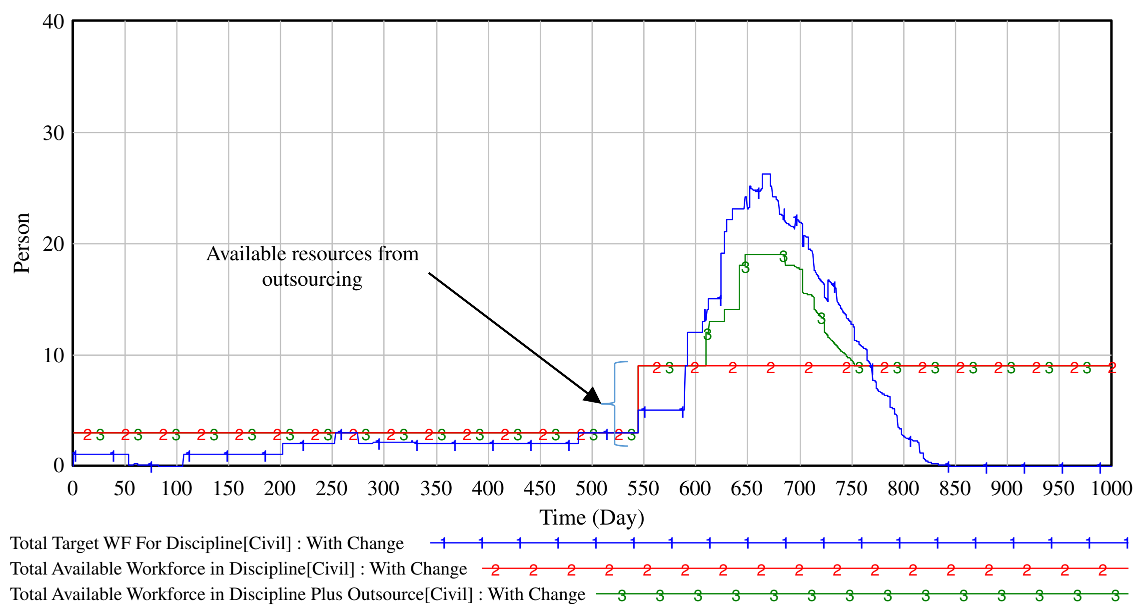

Fig. 11. Resource profiles for civil discipline under different policies.

Based on simulation results, reliability has been reduced due to hidden errors and latent changes in precedence activities. The predecessors of activity A_{43}, all of which are process activities, have been pending due to rework and delay. As a result, their reliability is reduced by the impact of scheduling pressure and increased overtime. By reducing reliability, more errors will be generated in these activities and, assuming that quality management accuracy is fixed, more of these errors will turn into hidden errors (Fig. 13). However, the accuracy of quality management is also reduced due to scheduling pressures, and thus more errors are created and become hidden.

As the hidden errors of activity A_1 and predecessors of activity A_{43} increase, the ripple effects caused by these errors will decrease the reliability of activity A_{43}. Fig. 14 shows the ripple effects of hidden errors of the predecessor's activities on activity A_{43}.

As can be seen, the hidden changes to predecessor activities have an adverse effect on the reliability of activity A_{43}. As noted previously, the occurrence of uncertainty in milestone specifications reduces the reliability of activities related to this milestone (predecessors of activity A_4). Decreasing reliability, as well as reducing the accuracy of the scope management due to the scheduling pressure, causes more hidden changes in these activities.

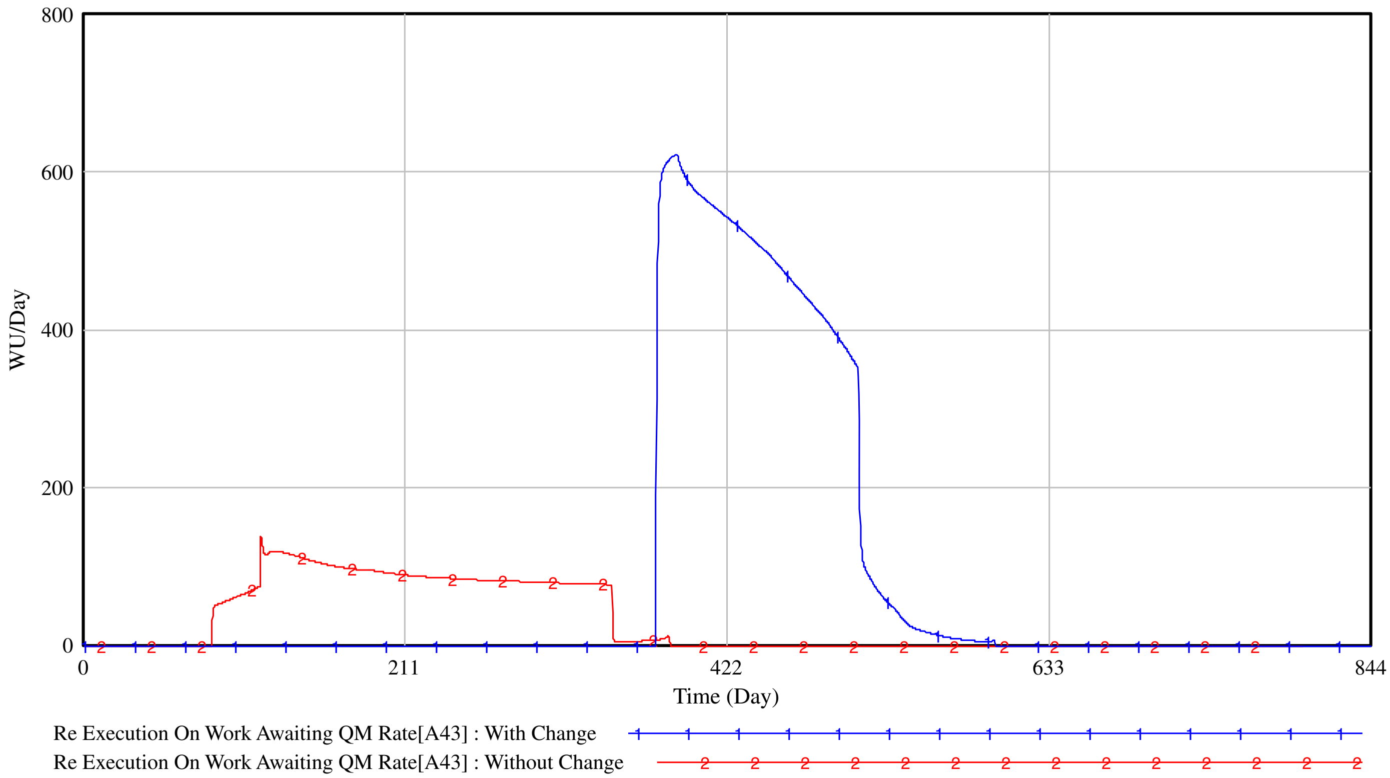

Fig. 12. Rework rate on work under quality control in the event of changes and without changes for activity A_{43}.

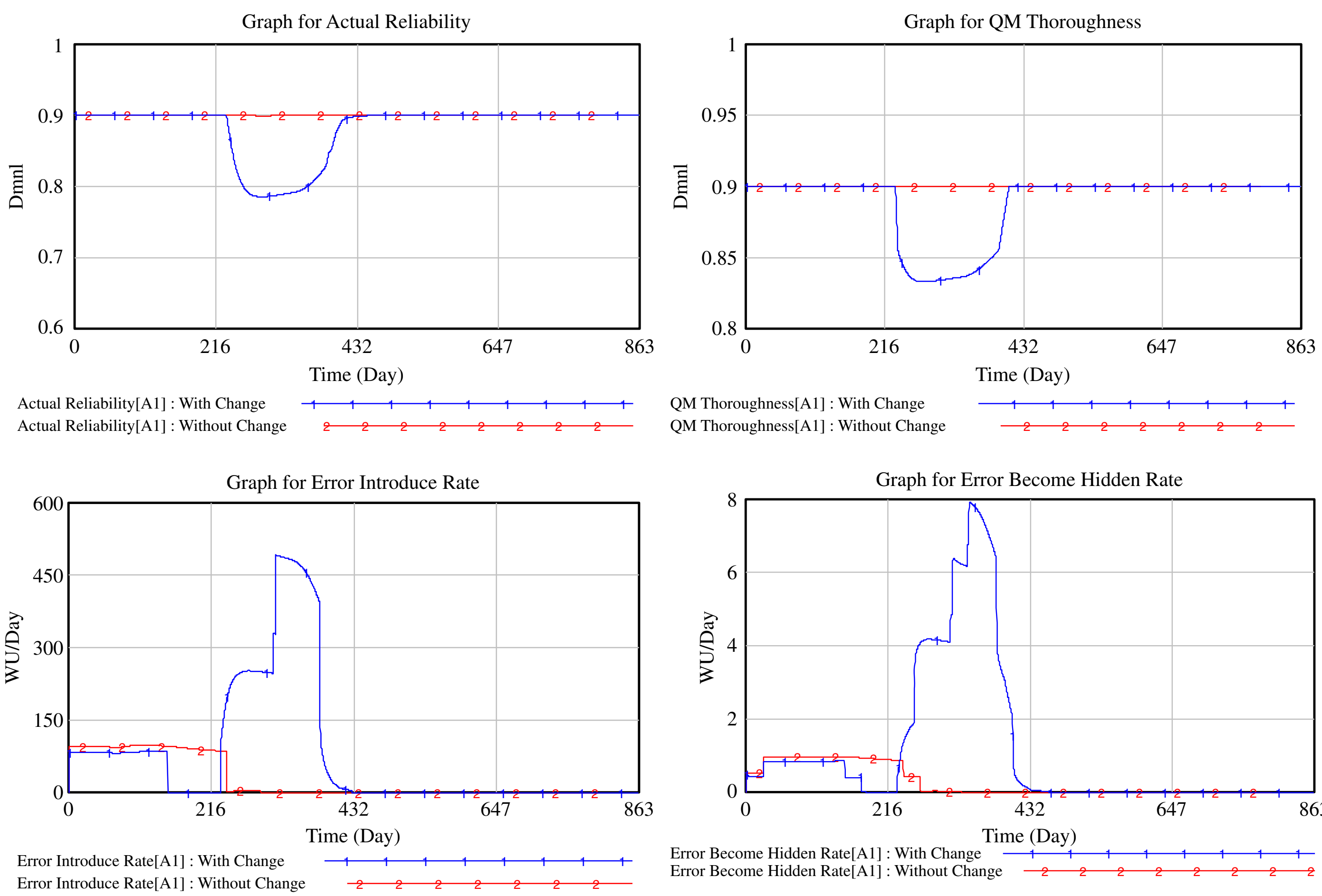

Fig. 13. Reliability chart, thoroughness of quality management, error rate, and rate of hidden errors for activity A_1.

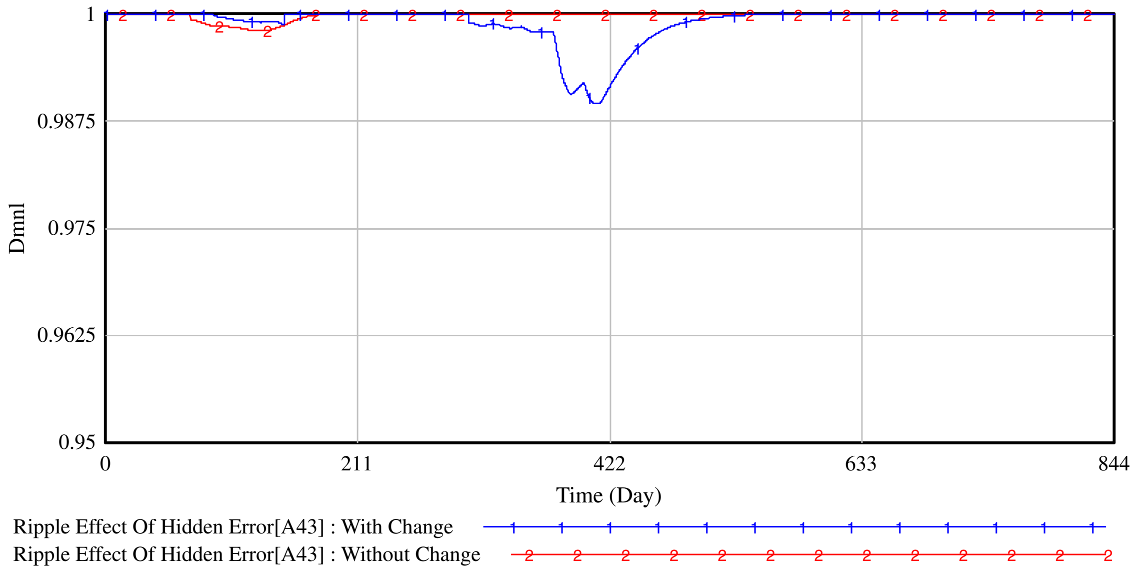

Fig. 14. Ripple effect of hidden errors on the reliability of activity A_{43}.

Fig. 15 shows the ripple effects of latent changes of predecessor activities on the reliability of activity A_{43}.

The loss of reliability of activity A_{43} will increase the rate of rework and slow down the progress of this activity. Also, the late start of activity A_{43} and the slowdown in its progress with regard to the start-to-start (SS) relationship with activity A_{69} delayed the start of this activity. Activity A_{69} should start on the 191st day according to the initial plan, but based on simulation results this activity began on the 450th day. Since this activity is associated with the next activity of this path (activity A_{85}) by an SS precedence relationship, the delay created at the start of this activity will delay the start of activity A_{85}. The delay in the start of this activity will also delay the start of the next activities to the end of the chain (activity A_{164}). Regarding activity A_{144}, civilian discipline, it can be concluded that due to lack of resources, the start of this activity has been delayed by 23 days.

Project Cost Analysis

As noted in the results of the previous section, the cost of completing the project at the request of changes by the employer is \$6.260 million. This cost increases by 25% compared to the project cost under the unchanged scenario. The main reasons for increasing costs in this case are as follows.

Project Delay

Due to the fact that IPMI uses permanent personnel, the project's delay will lead to continued employee salary costs. The total

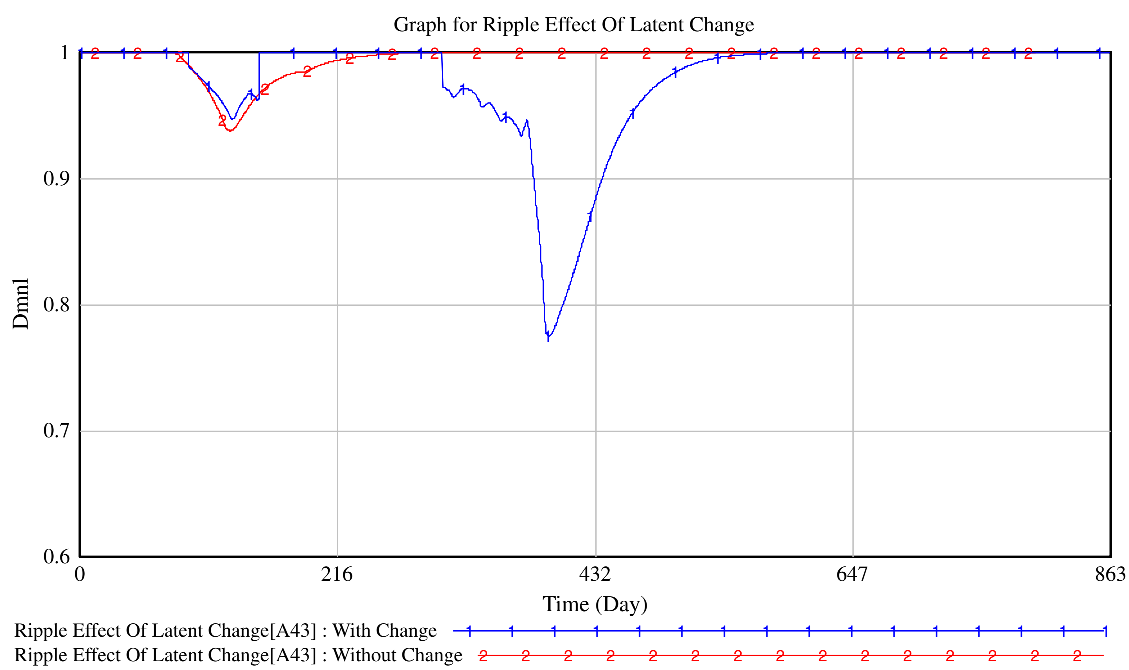

Fig. 15. Ripple effect of latent changes of the precedence activities on the reliability of activity A_{43}.

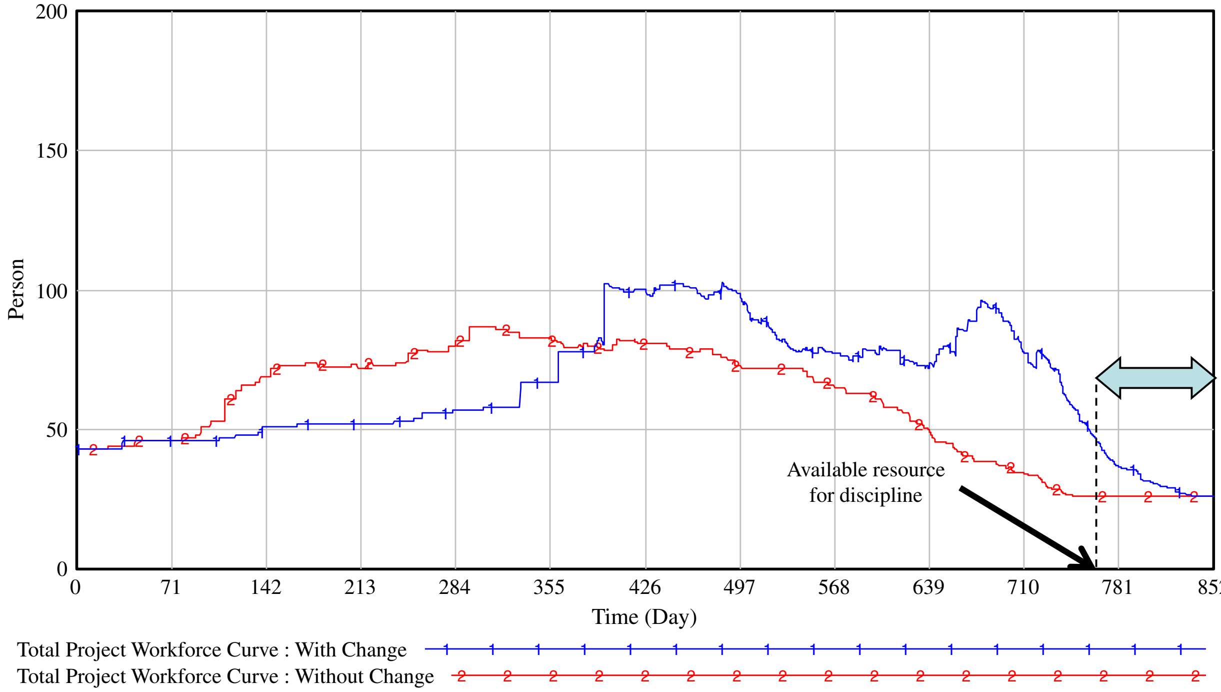

Fig. 16. Total project workforce curve under different scenarios.

number of personnel engaged in the project in the state of occurrence and the nonexistence of changes are the same because it is assumed that in the event of changes, the recruitment schedule is the same as normal. Personnel salaries have increased by $242,000 in cases of client-requested changes. Fig. 16 shows the human resources curve of the project in cases of changes and without changes. As can be seen in this figure, in the case of a change bid request, due to the reworks of process activities and the suspension of other activities related to these activities in other disciplines, fewer resources are actively engaged by these activities. By completing the key deliveries and enhancing process activities, more activity will be ready for accomplishment. At the end of the project, personnel costs have been increased by 92 × the daily cost in the normal case.

Increasing Overtime Costs

Given the changes made to the project and the schedule delay, more overtime is needed than normal. According to the obtained results, the extra overtime costs are $250,000 more than normal.

Increasing the Cost of Outsourcing Contracts

As already mentioned, the simulation results show that in a scenario without changes, the project can be completed on time without the need for outsourcing. But in the event of a change bid request, there is a situation where the amount of work increases for most disciplines and outsourcing becomes necessary.

Based on simulation results, outsourcing costs are $259,000 in the case of a change bid request. In total, there are 33 process activities in the project, of which 23 require complete or partial re-execution due to being in the interval before the key milestones. Of these, 13 are critical activities. In addition, 43 activities from other disciplines are related to these process activities. Due to the delay in doing these activities and the need for initiating in accordance with the original plan, more resources are needed. Fig. 17 illustrates the resource curves for different disciplines, where the resource usage peak (in the event of changes) is much larger than that of the case of no change.

Increasing Overhead Costs

Given that overhead costs are a multiplier of personnel salaries, personnel costs increase as overhead costs increase. Based on the simulation results, the extra overhead cost is $493,000. In addition to increasing project costs, another factor that reduces project profit (in case of changes) is the deduction from the performance guarantee due to the delay in completion of the project. The cost of the performance guarantee in this project is 5% of the total contract cost, amounting to $400,000. In the scenario of no change, where the project is completed on time, the total amount will be awarded to the contractor. But in the scenario of changes, due to a 92-day delay in completion of the project, about one-tenth of the original amount is calculated as a performance guarantee by the simulation model. Fig. 18 shows the cumulative incomes and fees paid during the project. As can be seen, between the 13th and 15th month of the project, the cumulative revenues of the project will be close to cumulative costs, which means reducing the project's current budget. This situation has occurred due to the slowdown of work and reduction of billing to the employer.

Project Quality Analysis

Based on the simulation results, in the case of no change, the project quality index is 0.9968. On the other hand, in the case of a change bid request, the project quality index equals 0.9976. The results show very little difference in the quality of the project. Accordingly, the project will be completed without having a high percentage error in the final product. Some of the quality indicators, such as the total error index, are related to the quality of work during the project time. As already mentioned, the total error rate is the ratio of total errors generated during the project for all project activities. Fig. 19 shows the total error in the project in different scenarios.

In the case of a change bid request, due to the increased scheduling pressure and increased overtime, the reliability of activities has decreased. As a result, more errors have been generated in the project. Increasing additional errors will cause further rework

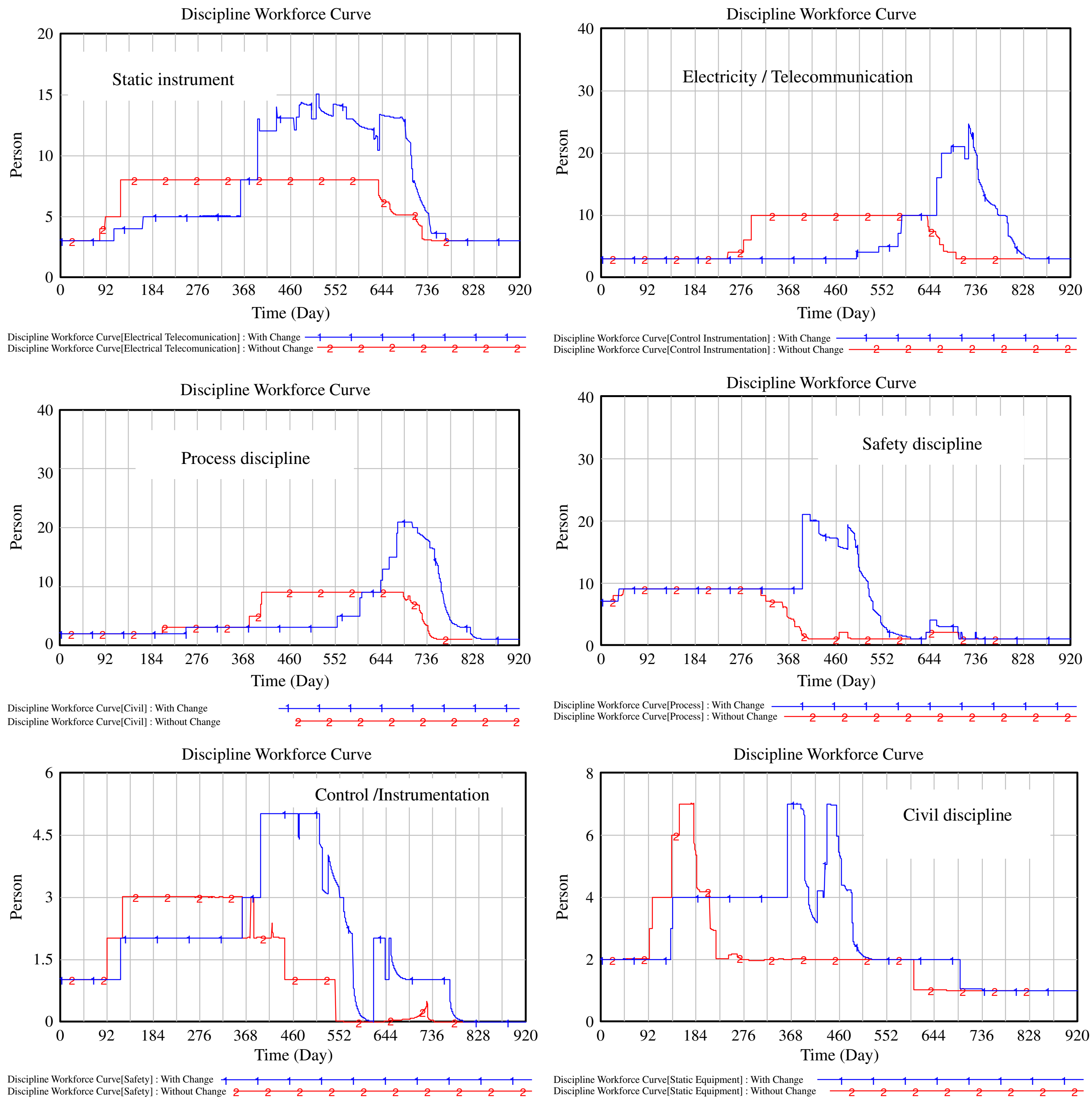

Fig. 17. Workforce profiles with and without changes.

in the project. As shown in Fig. 20, the ratio of rework in the scenario of changes requested by the employer (29.52%) is almost twice as much as the no-change scenario (15.40%).

Conclusion

In recent years, due to the growth of major construction projects involving oil, gas, and petrochemicals, there has been a lot of attention paid to project management techniques. Changes and rework, which in some cases are unavoidable, are among the issues that can affect the success of the project. Changes may result in a slowdown in the progress of work, quality loss, increased costs, delay, claims, and litigation. In the project management context, changes can characteristically affect the planned progress of the work. In this situation, the system dynamics are a valuable method for modeling the dynamic complexity and risks present in the project activities. Controlling these negative impacts through the implementation of change-management policies, especially in petrochemical projects, can be an effective step in preventing the loss of financial resources, workforce, and time. In the context of system dynamics and feedback loops, the application of control measures taken by project managers could lead to a reduction of latent errors and increase the reliability of the change-management decisions.

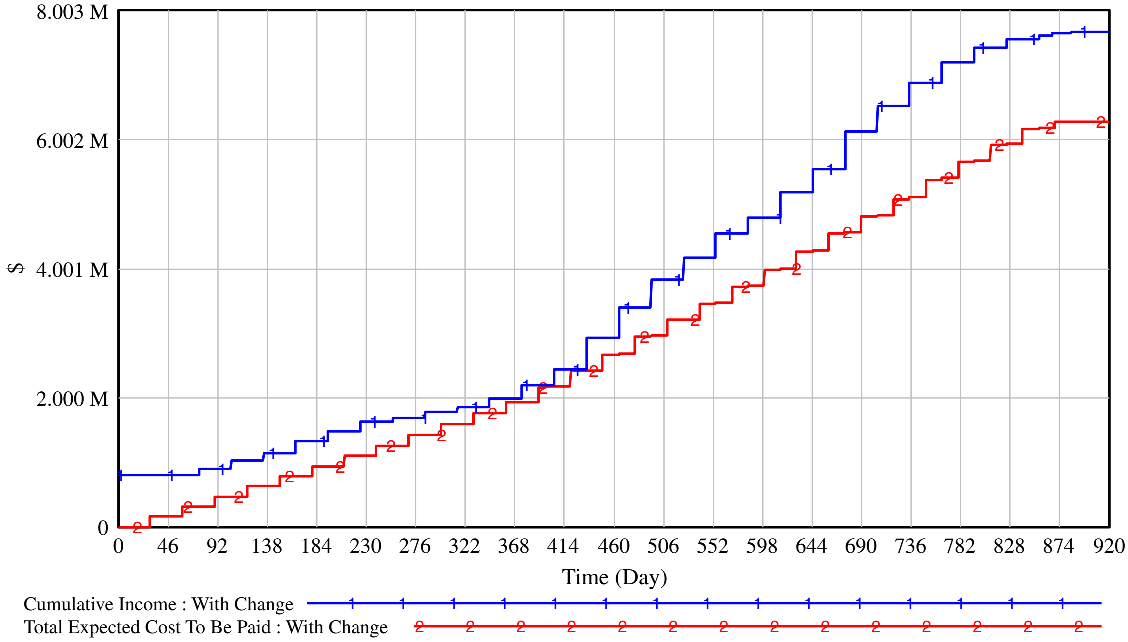

Fig. 18. Simulated income and total expected cost.

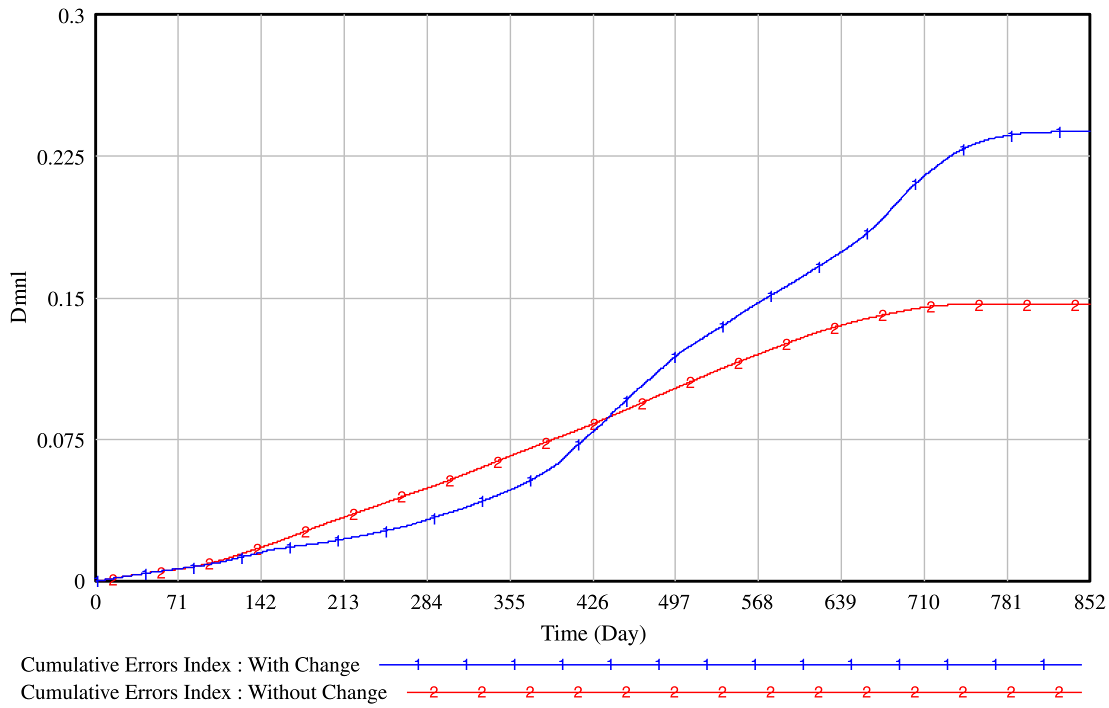

Fig. 19. Cumulative error index for project.

In this study, an integrated SD model was designed to analyze the future performance of the change-management policies. The model proposed is capable of performing risk analysis, taking into account factors such as the risk of the lack of resources, changes, and delays on the part of the client in reviewing and approving the work.

In order to validate the proposed SD model, a real case study of an engineering project was examined. The model was calibrated with data from an engineering project in the petrochemical industry. The policies include an extension of the project deadline, increasing the contract price, and plans to hire human resources and outsourcing. The result of the simulation illustrated that if both the employer and the contractor accept the increase in the contract price, then the project can be completed after 25 months with an increase of 54% in the hiring rate of human resources. In any case, even with financial compensation, the net present value of cash flows decreased by 22% for contractors compared to the case with the absence of changes.

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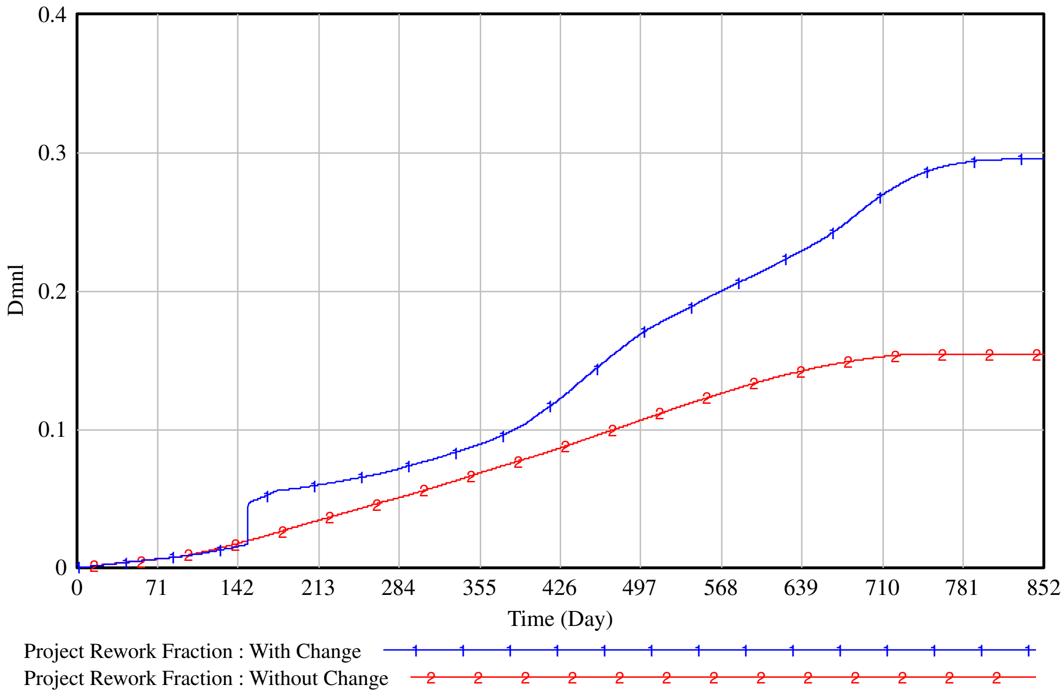

Fig. 20. Project rework fractions.

The results of the system dynamics model demonstrate its capability to effectively manage changes and errors. Based on the simulation results, if the project's extension policy is approved, the project can achieve predetermined goals with the current recruitment of a workforce. Based on the results, by reducing the employer's response time by 15 days, the duration of the project in the first policy (refunding) decreased from 773 to 751 days, and in the second policy (time extension), the duration of the project reduced from 945 to 921 days. However, due to the changes and prolongation of the project, the net present value of cash flows to the contractor will be reduced to \$1.5 million. By defining a pessimistic scenario, the robustness of time extension and reinvestment strategies along with human resources policies were tested. The simulation results showed that the project cannot be completed within 25 months. Instead, the policy of completing in 31 months without refunding can be achieved by readjusting the human resources recruitment plan and paying attention to critical activities in a pessimistic situation. Given the simulation results, if the probability of occurrence of a pessimistic scenario in reality is not unpredictable, the application of this policy will be less risky. In summary, the contributions of the present study can be itemized as follows:

- Development of a comprehensive and integrated system dynamics model consisting of scheduling, cost, quality, resources, changes, and cash flows to measure the impacts of change-management policies in the project;
- Modeling the causal structures related to overtime, hidden error, human resources productivity, and considering the variables that affect the rate of physical progress of the project; and
- Modeling the causal structure of project revenues influenced by outsourcing and human resources recruitment policies.

This study was restricted to a number of aspects described as follows:

- An important part of the input data were not available or were not in detail. The data gathering process was time consuming, so judgments were involved in the project. The time constraints in providing information as well as all organizational constraints resulted in some of the proposed structures not being fully consistent with the real facts.
- In the present study, the technique used to incorporate input data into the model was organized by spreadsheets and Excel files. If the number of activities and projects of the period studied is very large (several thousand), providing the information as the precedence relationship matrix will be very time consuming. In the case of such large projects, there should be possibilities for a direct data exchange between Vensim software and other software, such as Primavera and Microsoft Project.
- Considering the multiplicity of structures and models that use index variables and the number of variables comprised of more than 650 variables, the simulation time of a 900-day project takes about 45 min. The number of project activities has a significant impact on increasing the simulation time. The drawback of the relatively long simulation time in this study was the time constraint to test various improvement policies.

To further advance research in the area of schedule management and to improve the effectiveness of the framework proposed, future research should be carried out focusing on increasing the transparency of the uncertainty metrics to better assess the magnitude of the effects of various uncertainties and on increasing the number of activity execution modes to better reflect how activities are performed in practice and to enrich the options that project teams have in adjusting resource profiles.

The SD model in this research was developed to control a contract engineering project. Obviously, the development of the model's structure so that it can engage in activities such as construction and purchasing will be very valuable. The areas that can be applied to the development of causal loop structures are the study of the effect of scheduling pressure on accepting changes, the effect of budget deficits on the intention to make deliberate changes by the contractor, and the effect of coordination and experience of the workforce on the reliability and sustainability of the activity as well as time, cost, and quality trade-offs in the project.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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