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A Dynamic Model of Procurement Risk Element Transmission in Construction Projects

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Abstract The cost of materials is the largest proportion of a construction project's total budget. If the materials cannot be delivered to the construction site on time, completely and with acceptable quality, the project's duration and cost will be greatly affected. Based on the generalized project risk element transmission theory and system dynamics, a system dynamics model was developed to capture dynamics of procurement risk elements transmission during construction projects and how various procurement risk elements affect the project's duration and cost by simulation. In this paper, procurement risk element is considered as the uncertain factors in procurement. Based on these results, it is concluded that the developed model can provide important information for risk managers and project managers addressing procurement risk.

Keywords procurement risk; risk management; risk element transmission; construction project; system dynamic

1 Introduction

The construction industry provides the basic living conditions for the sustainability and development of human life on the earth[1]. The cost of materials is the largest portion of a construction project's total budget. The proportion recognized by the industry is approximately 60%–70% and possibly even more in some projects. Thus, the ability of construction managers to manage procurement effectively will directly affect the project's budget. As construction projects increase in size and scope, the material procurement demand increases, the construction period is longer, the project environment is more complex and the accuracy of the materials' delivery time becomes more important. All of these factors make project procurement risk

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more complicated. Risk is exposure to the consequences of uncertainty that will affect project objectives[2]. If the procurement risk occurs during the project's planned duration, project managers will be forced to extend the project period and to increase costs, thus result in project management objectives impossible to achieve.

In project risk management, many different models, tools and techniques were studied and used[3]. The problem of structure optimization in project purchasing management is essentially how to determine the number of suppliers. The number of suppliers is related to the supply risk and total purchase cost[4]. From the system dynamics angle, Fu et al. analyzed the set of risk factors for the project of material supply chain and provides a fuzzy method for measuring the whole supply chain risk[5]. Organizations undertake strategic supply chain initiatives through project implementation. However, selecting the appropriate supply chain projects can be difficult due to high levels of organizational risk and technical complexity[6]. Terrés et al.[7] have undertaken an exploratory analysis of the extrinsic and intrinsic factors affecting an employer's safety motivation in the construction industry. Barker and Haimes[8] proposed a quantitative risk analysis framework to measure the sensitivity of the consequences of extreme events to the uncertainty parameters of the basic probability distribution. This approach eliminated the human influence factor in the expert assessment method and had a good effect on decision making on risk. Balbás et al.[9] transformed the risk function into an infinite-dimensional Banach space of linear programming and gave the general simplex algorithm, which worked well in investment portfolios and the optimal hedge. Other methods, such as artificial neural networks[10], genetic algorithms[11], Monte Carlo simulation[12], risk assessment[13] and multi-agent[14], were used to solve project risk problems. Tsang and Zahra[15] suggested that the causes and effects of errors are not unidirectional or linear but rather are reciprocal and looped in their relationships. In the effort to reduce errors and rework, it is necessary to understand how such relationships emerge and interact with one another[16]. Cifre et al.[17] assessed the effectiveness of a work stress intervention to increase job and personal resources and to consequently reduce job strain and increase employee psychosocial well-being in an enamel manufacturing company following the Resources-Experiences-Demands Model and within the Action-Research approach.

Much research has been conducted regarding risk management, and the related theories are mature, but the research on how risk factors affect each other in projects is insufficient. This paper aims to develop a system dynamics model, which is based on the definition of risk element transmission influence as the model purpose and the construction cost and duration as the system boundary. The feedback loop of interrelated factors in projects was described, and system dynamics was used to establish a risk analysis model. Finally, by model simulation, the results of different situations were contrasted to verify the existence of risk elements and examine the effect of the risk elements on the project examined. The results can offer a better understanding of the complex mechanisms of procurement risks and how they damage project performance.

2 Research Methodology

2.1 System Dynamics

System dynamics (SD) has a long history as a modeling approach with its origin in the work of Forrester[18], who developed the subject for the analysis of complex industrial systems[19]. System dynamics describes cause-and-effect relationships with stocks, flows and feedback loops[20]. Stocks and flows are used to model the flow of work and resources through a project[21, 22]. The risk allocation process is affected by multiple interdependent factors that are highly dynamic, involve multiple feedback processes, and nonlinear relationships with both hard (quantitative) and soft (qualitative) data[23]. System dynamics is a popular approach to studying such problems for its ability to deal with high levels of uncertainty and causal ambiguity and to describe how systems evolve over time[24]. System dynamics is suitable for modeling such a highly dynamic system and may be easily applied to simulate these multiple interdependent components[2].

2.2 Risk Element Transmission

Li[25] defined the basic risk variables as risk elements and proposed that the project objectives (such as duration and cost) often fluctuate with the random fluctuation of risk elements. This type of transmission is called risk transmission. Furthermore, a three-dimensional model of generalized project risk element transmission theory, in which a risk element transmission analytical model was proposed to study the transmission impact of the project period risk element, was introduced[26].

3 The Causal Analysis of a Procurement Risk Element Transmission System

Regardless of an individual's skill level, experience or education, errors may occur at any time due to the physiological and psychological limitations of humans[27]. Unfortunately, some deviation from management objectives will occur regardless how perfect the management methods are and how mature the management technologies are. In project management, although there are strict management measures and adequate inspection in the procurement process, the procurement risk element still appears. Some risk elements may be substandard quality, the wrong type of material, or failure to meet the acceptance criteria. If substandard materials are used in construction, the unqualified quantities associated with them will be detected eventually, meaning that the material quality risk element is generated within the procurement risk element. Triggered by these procurement risks, the total exceeds the planned quantity, then the construction labor charges, the project duration and the reworking material cost must be adjusted.

Generally, to ensure the quality of materials and timely supply, the procurement contract for the materials required in the project will be signed before the construction begins. However, the following situations will introduce the time risk element in the procurement: The planned procurement materials arrive later than expected, or the procurement of additional materials due to the increased quantities causes a delay. The time risk element means that the amount of material in inventory cannot keep pace with the planned construction speed, and the actual construction speed will fall below the planned pace. In this condition, the project will be delayed.

Price is another risk in the procurement process. Accompanied by changes in supply and demand of the market economy, price risks will happen although contracts are put in place to keep the price within the budget. Especially in large construction projects, with larger quantities and longer durations, the materials cost accounts for a large portion of a construction project, it is quite difficult for project managers to keep the total cost within the original budget by cutting other costs when the price of materials rises. This will lead the project costs to surpass the budget directly.

Given the boundary of the system, ways to adjust the budget and offering overtime to speed up the construction have not been covered in this research. The causal relationship of how the procurement risk element affects the duration and cost is reflected in Figure 1.

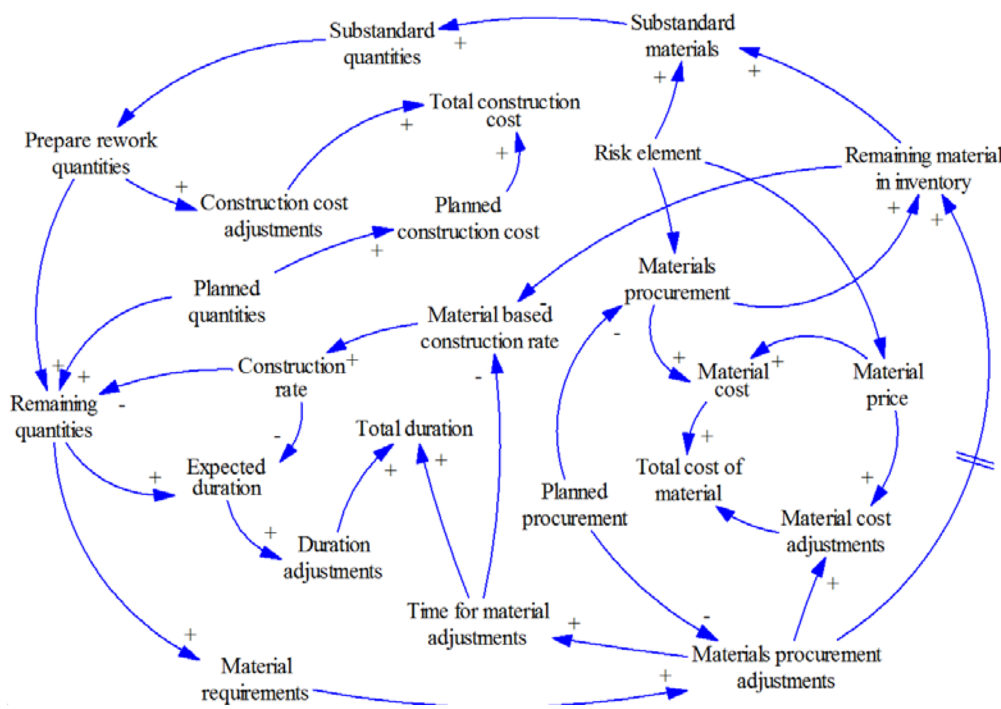

Figure 1 Procurement risk causal loop diagram

4 System Dynamics Modeling

Based on the above analysis, a system dynamics model of the procurement risk element transmission was built via an SD software, Vensim, as shown in Figure 2. The model includes five subsystems composed of 58 variables; only a part of the main functional formula is described. If the materials can be delivered to the construction site completely, economically, and with acceptable quality in accordance with the construction schedule, and the inventory level can be maintained, the project will proceed as scheduled.

1) When the construction reaches the $X1$th day, substandard materials arrive in the construction site and begin to be used in the construction, and unqualified quantities start to emerge. Eventually, the substandard materials are detected and the corresponding quantities

are also determined to be unqualified. The unqualified quantities need to be reworked. If the required amount of materials for the reworked quantities and remaining quantities is greater than the remaining planned quantities, it is necessary to repurchase a certain amount of materials to refund the balance. The expression of material procurement adjustment follows:

$$\begin{aligned}
&Material\ procurement\ adjustments\ rate\\
=&\text{IF THEN ELSE}((Remaining,\\
&planned\ quantities + Prepare\ rework\ quantities) * Material\\
&consume\ per\ unit\ quantity - Materials\ purchase\\
&order\ adjustments - Material\ in\ inventory - Remaining\\
&planned\ procurement > 0, (Remaining\ planned\ quantities\\
&+Prepare\ rework\ quantities) * Material\ consume\ per\ unit\\
&quantity - Material\ in\ inventory - Remaining\ planned\ procurement, 0)
\end{aligned} \tag{1}$$

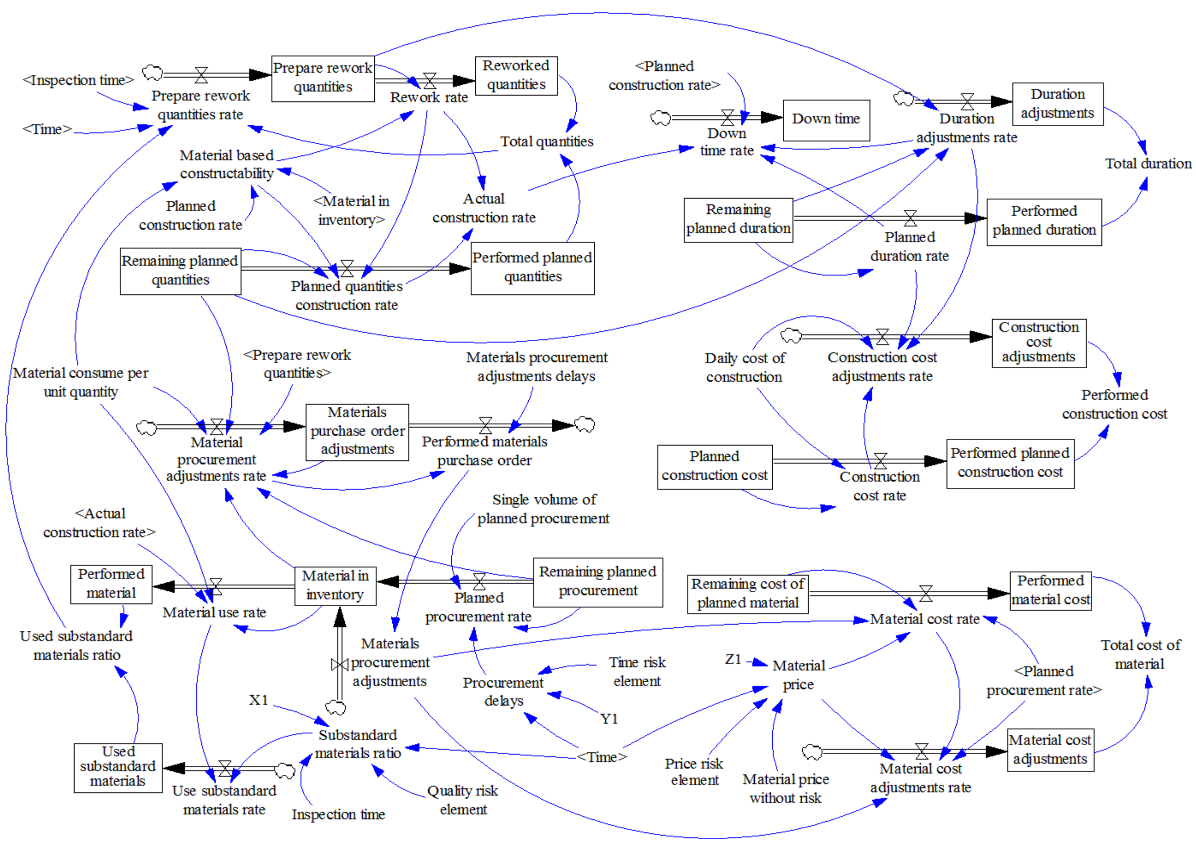

Figure 2 Stock and flow diagram for procurement risk element transmission

2) There is a time delay for the adjusted material procurement, from procurement order confirmation to the materials' arrival at the construction site. In addition, the length of a time delay usually varies by project and circumstance. In this paper, the delay time is set to be an

adjustable constant. The expression of the procurement order delay follows:

$$\begin{aligned} &Performed\ materials\ purchase\ order = \text{DELAY FIXED}(Material\ procurement \\ &\quad adjustments\ rate, Materials\ procurement\ adjustments\ delays, 0) \end{aligned} \tag{2}$$

3) After the change of procurement order, as the actual total procurement volume exceeds the planned volume, the actual procurement cost will also exceed the planned cost. In this case, the material procurement cost of the project should be adjusted. The expression of the material procurement cost adjustment follows:

$$\begin{aligned} &Material\ cost\ adjustments\ rate = (Planned\ procurement\ rate\ + Materials \\ &\quad procurement\ adjustments) * Material\ price - Material\ cost\ rate \end{aligned} \tag{3}$$

4) Due to the increased rework quantities, the total quantities cannot be completed on time at the planned speed. Some scholars have researched the approaches of employees working overtime and increasing labor, but in this paper, we only take into account a linear duration extension. When the remaining planned duration is inadequate for the remaining quantities, the duration adjustment is expressed as follows:

$$\begin{aligned} &Duration\ adjustments\ rate = \text{IF THEN ELSE}(Remaining\ planned\ duration < 1, \\ &\quad \text{IF THEN ELSE}(Prepare\ rework\ quantities > 0 : \text{OR} : Remaining \\ &\quad planned\ quantities > 0, 1, 0), 0) \end{aligned} \tag{4}$$

5) During the project, the actual construction speed will decrease because of the shortage of materials inventory, but the costs of labor and machinery are still paid according to the original budget based on the planned speed. When the actual duration is longer than the planned duration, the planned construction cost cannot cover the actual construction cost. Thus, the construction cost should be adjusted according to the following expression:

$$\begin{aligned} &Construction\ cost\ adjustments\ rate = \text{IF THEN ELSE}(Duration\ adjustments \\ &\quad rate > 0 : \text{OR} : Planned\ duration\ rate > 0, Daily\ cost\ of\ construction \\ &\quad - Construction\ cost\ rate, 0) \end{aligned} \tag{5}$$

6) When the construction reaches the $Y1$th day, the time delay occurs in the procurement process and the required materials cannot be delivered to the construction site according to the planned schedule. From this moment, because the inventory cannot match the planned construction speed, the actual construction speed will be limited. The expression of the limited construction capacity is as follows:

$$\begin{aligned} &Material\ based\ constructability = \text{MIN}(Planned\ construction\ rate, Material\ in \\ &\quad inventory/Material\ consume\ per\ unit\ quantity) \end{aligned} \tag{6}$$

7) During the construction, labor force idling occurs if the actual construction speed is lower than the planned speed because of inadequate material supply. That is, because of the shortage of construction materials, the machinery and workers have to be idled. The expression of labor force idling follows:

$$Down\ time\ rate = \text{IF THEN ELSE}(Planned\ duration\ rate > 0 : \text{OR} : Duration$$

$$adjustments\ rate > 0, Planned\ construction\ rate - Actual$$
$$construction\ rate, 0) \quad (7)$$

8) The procurement price rises when the construction reaches the $Z1$th day. This will cause the actual procurement expense to be higher than the planned cost. The material procurement cost adjustment is Formula (3).

5 The Analysis of Examples

5.1 The Explanation of Parameter Settings

Based on data sourced from Chinese construction projects, Table 1 exhibits some of the parameter settings in this model. We can adjust them depending on the different project types and scales, which will not have an undesirable impact on the robustness and accuracy.

Table 1 List of variables

ID	Parameters	Ranges	Units	Values
1	$X1$	$[0, Duration]$	day	
2	$Y1$	$[0, Duration]$	day	
3	$Z1$	$[0, Duration]$	day	
4	$Quality\ risk\ element$	$[0, 1]$	unitless	
5	$Time\ risk\ element$	$[0, \infty]$	day	
6	$Price\ risk\ element$	$[0, \infty]$	unitless	
7	$Inspection\ time$	$[X1, Duration]$	day	
8	$Material\ price\ without\ risk$	$[0, \infty]$	yuan/unit material	6
9	$Cost\ of\ planned\ material$	$[0, \infty]$	yuan	1200000
10	$Material\ consume\ per\ unit\ quantity$	$[0, \infty]$	unit material/unit task	80
11	$Remaining\ planned\ procurement$	$[0, \infty]$	unit material	184000
12	$Material\ in\ inventory$	$[0, \infty]$	unit material	16000
13	$Materials\ procurement\ adjustment\ delays$	$[0, \infty]$	day	4
14	$Single\ volume\ of\ planned\ procurement$	$[0, \infty]$	unit material	4000
15	$Remaining\ quantities$	$[0, \infty]$	unit task	2500
16	$Remaining\ planned\ duration$	$[0, \infty]$	day	50
17	$Planned\ construction\ rate$	$[0, \infty]$	task/day	50
18	$Daily\ cost\ of\ construction$	$[0, \infty]$	yuan/day	15000
19	$Planned\ construction\ cost$	$[0, \infty]$	yuan	750000

5.2 Simulation and Analysis

1) This part simulates a situation in which the procurement risk element did not occur; that is, the procurement risk element was 0. This is shown in Figure 3. From the figure, the objectives of this project have been reached on the planned schedule, and every curve stays smooth, and no stagnation or jumping emerges. The quantities are completed entirely on the

last day, and there are no remaining quantities. The construction and material costs are used according to the planned schedule, and there are no overruns.

2) The procurement risk occurs when the construction reaches the 5th day, and on the 9th day, it was detected that 30% of materials used in the construction are substandard, as is shown in Figure 4. The project duration was 52 days, and the delay time was 2 days. The rework quantity was 75 units, and the total completion quantity was 2575 units. The construction cost was 78 million yuan and exceeded the budget by 3 million yuan; the material cost was 123.6 million yuan and exceeded the budget by 3.6 million yuan. Because the remaining quantities of the last day were less than the construction capacity, 25 units of idling quantities were produced.

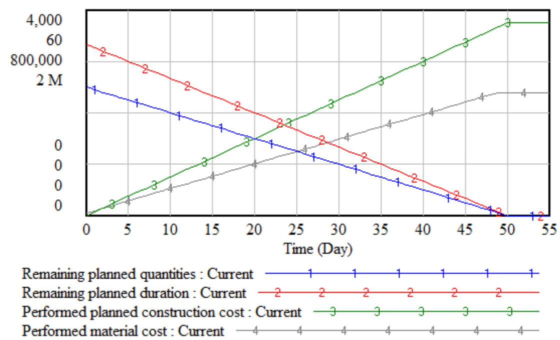

Figure 3 Simulated result without risk element

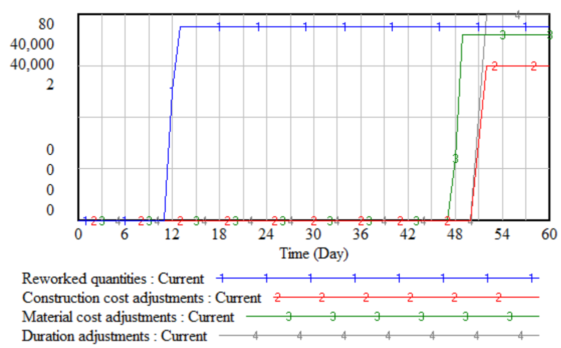

Figure 4 Simulated result on the 5th to 9th days with substandard materials =30%

The procurement risk occurs when the construction reaches the 5th day, and on the 9th day it was detected that all materials used in the construction were substandard, as is shown in Figure 5. The project duration was 55 days, and the delay time was 5 days. The rework quantity is 250 units, and the total completion quantity was 2750 units. The construction cost was 82.5 million yuan and exceeded the budget by 7.5 million yuan; the material cost was 132 million yuan and exceeded the budget by 12 million yuan.

The procurement risk occurs when the construction reaches the 44th day, and on the 48th day, it was detected that all the materials used in the construction were substandard, as is shown in Figure 6. The project duration was 59 days, and the delay time was 9 days. The rework quantity was 250 units, and the total completion quantity was 2750 units. The construction cost was 88.5 million yuan and exceeded the budget by 13.5 million yuan; the material cost was 132 million yuan and exceeded the budget by 12 million yuan. Because the delay time of the rework material procurement was longer than the remaining duration of the project, it had to be extended. In addition, the lack of inventory resulted in lower actual construction speed, and 200 units of idling engineering were produced.

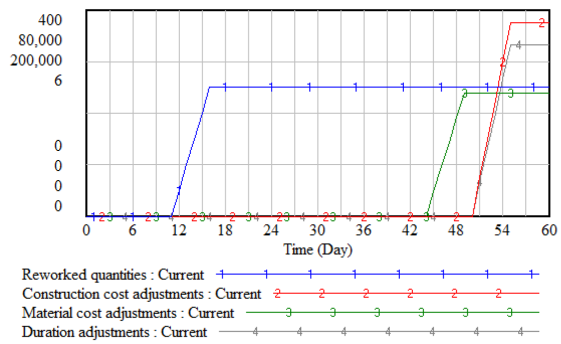

Figure 5 Simulated result on the 5th to 9th days with substandard materials =100%

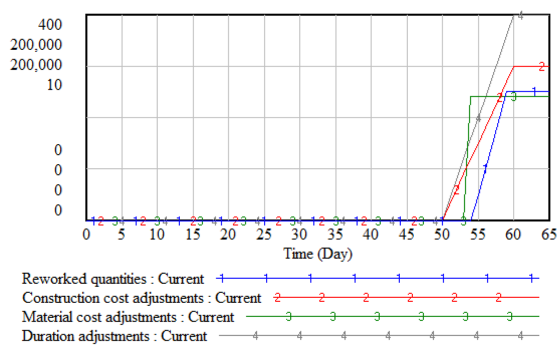

Figure 6 Simulated result at 44th to 48th day with substandard materials =100%

3) The procurement risk occurs when the construction reaches the 10th day, and the materials reached the construction site later than the expected time of 5 days, as is shown in Figure 7. The project duration was 55 days, and the delay time was 5 days. The total completion quantity was 2500 units. The construction cost was 82.5 million yuan and exceeded the budget by 7.5 million yuan, and the material cost was 120 million yuan. Because the construction speed was limited by the lack of inventory, 250 units of idling quantities were produced.

4) The materials reached the construction site later than the expected time of 4 days when the construction reaches the 5th day, the procurement risk occurs on the 10th day, and on the 16th day, it was detected that all materials used in the construction were substandard. The materials price rose by 30% on the 20th day. Figure 8 reflects this situation. The project

duration was 61 days, and the delay time was 11 days. The rework quantity was 350 units, and the total completion quantity was 2850 units. The construction cost was 91.5 million yuan and exceeded the budget by 16.5 million yuan; the material cost was 165.6 million yuan and exceeded the budget by 6.5 million yuan. Two-hundred units of idling quantities were produced.

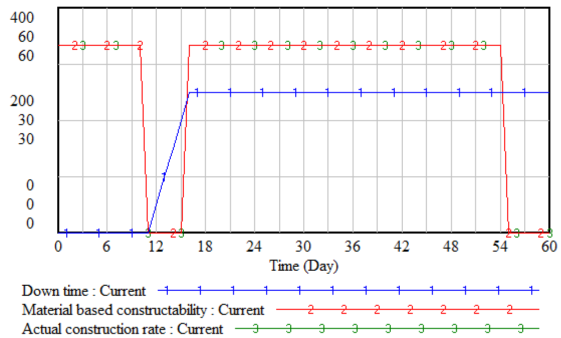

Figure 7 Simulated result on the 10th day with materials delayed arrival =5

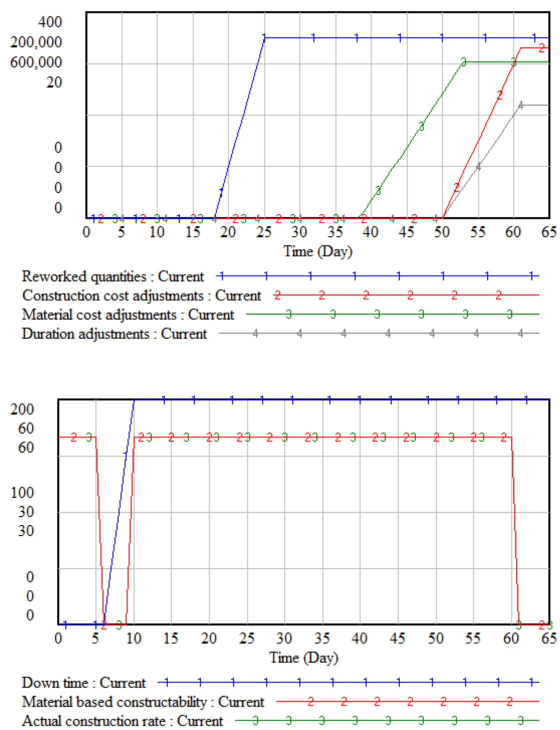

Figure 8 Simulated result of multiple risk element

6 Conclusions

Application of the model to construction project confirmed that the procurement risk elements generated during construction will influence the quantities, cost and duration of the project. Given these circumstances, in this paper, we develop a SD-based model of the risk element transmission that simulates how the procurement risk elements affected the scope and depth of the project. We can draw the following conclusions from the simulations.

1) This paper strode a meaningful step is that the risk element transmission theory was introduced into the process of how the procurement risks impact the construction project and transfer, this makes us to conduct a quantitative analysis on the procedure and level.

2) When the material quality is below standard, there will be rework quantities. The later the poor quality is detected and the more unqualified completed quantities there are, the more rework quantities there are. In addition, the demand of construction materials for rework and the material cost also increase. Accordingly, the construction cost and duration corresponding to the rework quantities increase.

3) When the delay time for adjusting a procurement order is longer than the remaining duration, the arrival of the material at the construction site will result in a delay.

4) When the amount of inventory is insufficient, construction will be limited and the actual construction speed will be slower. This means that labor force idling will occur.

5) During the duration of the project, the later the change of the procurement price happens, the less the impact on the material cost will be.

We can research the following aspects further: the various types of materials that can be used in construction and the effects of different material types on the project.

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