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SYSTEM DYANMICS APPROACH FOR ERROR AND CHANGE MANAGEMENT IN CONCURRENT DESIGN AND CONSTRUCTION

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ABSTRACT

Errors and changes, particularly in concurrent design and construction, require a careful approach to their management, since they can generate unanticipated impacts on construction performance, which is often related to softer aspects of management (e.g., fatigue). Focusing on this issue, this paper explores the use of system dynamics in identifying multiple feedback processes and softer aspects of managing errors and changes. Applying the developed model into the design-build highway project in Massachusetts, this paper concludes that the system dynamics approach can be an effective tool in the understanding of complex and dynamic construction processes and in supporting the decision making process of making appropriate policies to improve construction performance.

1 INTRODUCTION

Errors and changes are very common and are one of the major driving factors to make construction uncertain (Lee et al. 2003a). The impact of error or change could propagate to other activities, through physical and procedural relationships and, are not always identified promptly. As a result, the monitored performance may not follow the planned performance and is not able to capture the existence of hidden errors (i.e., errors that are not identified through the quality management process) or latent changes (i.e., changes that are not identified through the scope management process) (Lee et al. 2003a). Consequent symptoms are produced, which include chronic schedule and cost overrun, despite advancements in construction equipment and management techniques (Park and Peña-Mora 2003). This situation worsens when concurrent design and construction is applied, because of an overlap of activities which shorten project duration. Concurrent design and construction often require that succeeding activities have to proceed without complete information from preceding activities. Also, the decision making process to deal with errors and changes can be accelerated due to the pressure from this shortened time frame.

It is also difficult to manage errors and changes because of the dynamics and complexities of multiple feedback processes of the softer aspects of project management, such as fatigue or moral. In this context, the Dynamic Planning and control Methodology (DPM), which incorporates a System Dynamics (SD) model as a core simulation engine, has been developed to assist in the preparation of robust construction plans and to provide policy guidelines to handle such negative impacts of errors and changes (Park and Peña-Mora 2003, Lee 2003). Rather than applying Discrete Event Simulation (DES) that has been widely used in the construction domain, this paper discusses the modeling of the construction process associated with error and change management, using SD, which has been renowned for its capability to address feedback processes as a way to understand system structure.

The goal of this research is to understand the impact of errors and changes on construction performance, in order to assist the policy making process based on the attained understanding of errors and changes.

2 FEEDBACK PROCESSES

There are two types of feedback processes in the system: the reinforcing feedback that amplifies whatever is happening in the system and the balancing feedback that counteracts and opposes change (Sterman 2000). All dynamics arise from the interaction of these two types of feedback process among the components of the system, not from the complexity of the components themselves (Sterman 2000). Figure 1 illustrates how errors and changes generate these feedback processes during actual execution.

Suppose errors and changes are introduced, and an additional work amount is added to the original work scope to address errors or accept changes. In order to deal with this additional work scope, a manager may adopt overtime for a workforce as a control action to maintain a planned schedule. The adoption of overtime can contribute to increasing the amount of work being performed; thereby, resolving any negative repercussions due to the additional work amount caused by errors and changes (the effect of the balancing loop in Figure 1). However, prolonged work hours could increase fatigue and deteriorate the workforce's morale. This deterioration of morale and increased fatigue could negatively affect the workforce's productivity and the quality of work, therefore generating additional errors and changes (the effect of the reinforcing loop in Figure 1) (Sterman 2000, Lee et al. 2003b). This coexistence of different feedback processes also explains the softer aspects associated with error and change management (e.g., fatigue and morale).

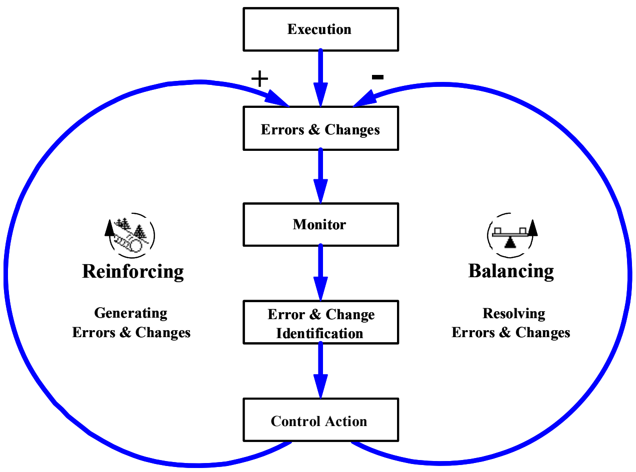


Figure 1: Multiple Feedback Processes

In most cases during actual execution, errors and changes add additional work and as a result, the actual work scope becomes greater than the initial scope. Furthermore, this additional work scope on one activity could affect other activities due to their dependencies, which is known as the ripple effect. This scope gap is one of the main sources for feedback processes. In other words, every designed action for maintaining quality and productivity was based on the initial work scope that was identified in the planning stage. However, the intended quality and productivity may be difficult to be maintained with an increased work amount. Suppose a project has an initial work amount which takes 10 days, with 10 workers, to accomplish it. If additional 10% of the initial work amount is added due to errors, a schedule delay will be experienced since the intended productivity calls for 11 days, with the existing 10 workers. However, this schedule slippage could be avoided by taking control actions (e.g., overtime). As illustrated in Figure 1, control actions, which are not originally planned, may generate multiple feedback processes including side effects. In addition, these unanticipated effects become more detrimental when concurrent design and construction is applied.

3 SYSTEM DYNAMICS MODEL

Considering all the characteristics of errors and changes, a system dynamics project model has been developed (Park and Peña-Mora 2003, Lee 2003). It is customized and enhanced from existing project models (Cooper 1980, Richardson and Pugh 1981, Abdel-Hamid 1984, Ford and Sterman 1998, Lyneis et al. 2001), in order to study the unique characteristics of errors and changes in concurrent design and construction.

3.1 Basic Work Process Model

Before focusing on the detailed model, Figure 2 shows the basic 'work execution' structure in SD. After conceptualizing the model structure, as illustrated in Figure 1, the next step of SD modeling is model formation, which includes the identification of stock and flow structure as seen in Figure 2. Stock and flow structure characterizes the state of the system and generates the information upon which decision and actions are based, by giving the system inertia and memory (Sterman 2000). Stocks represent stored quantities, and flows represent control quantities flowing into and out of stocks (Peña-Mora and Park 2001). Figure 2 shows highly a simplified stock and flow structure for 'work execution'. Before execution, all tasks are in the stock of 'Work To Be Done'. Based on the number of people and productivity which can vary over time (i.e., flow of 'Work Being Done'), tasks in 'Work To Be Done' can move into the stock of 'Work Done', which means tasks are completed.

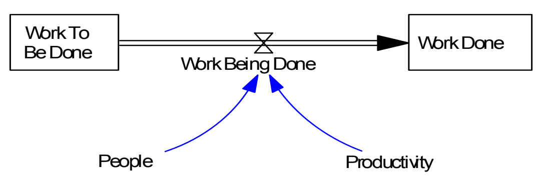


Figure 2: Basic Work Execution in SD

3.2 Generic Process Model Structure

Extending this simplified stock and flow structure, the developed model, first, captures the generic construction process and then, the identifies characteristics of errors and changes which are embedded in the model structure, as seen in Figure 3. The distinct feature that the current model has is that the model explicitly represents the change management process in design and construction, linking with the quality management process and the request for information (RFI) process.

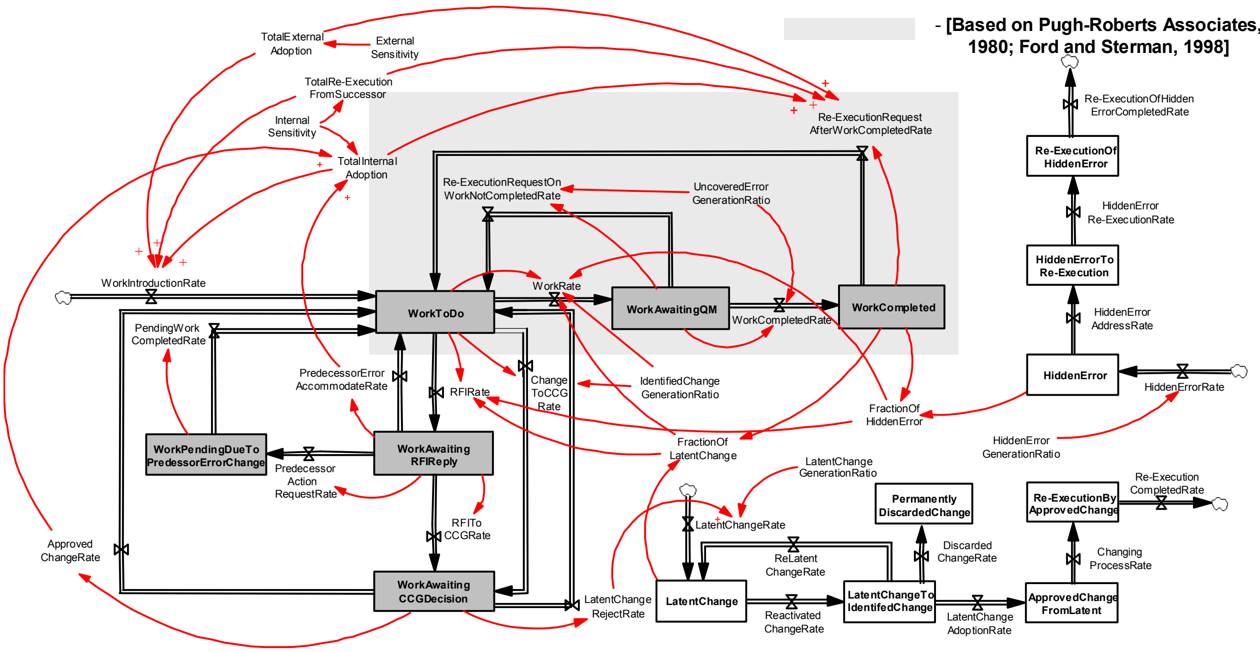


Figure 3: Generic Process Model (Based on Pugh-Roberts Associates 1980, Ford and Sterman 1998)

For example, the change management process is modeled as shown in Figure 4. Managing changes in design and construction usually have two major components, the Scope Management (SM) process and the Claim and Change Management (CCM) process. The SM process can be summarized as the review process and the CCM process, as the decision making process (e.g., adoption or rejection of changes). Specifically, before the execution of a task, the scope management (SM) process is applied to the stock of 'WorkToDo' (WTD), as denoted by A in Figure 4. The SM process aims to make sure that the given scope of work and the corresponding work setting are the same, as specified in drawings and specifications. Thus, if this 'WTD' stock differs from the originally planned 'WTD' stock, those tasks in 'WTD' stock are sent to the stock of 'WorkAwaitingCCMGDecision' (WACCMGD - B in Figure 4), which needs the decision or analysis of Claim and Change Management (CCM) group.

However, some potential changes may not be identified (i.e., latent changes) during the SM process. In this sense, Scope Management THoroughness (SMTH) is defined as the degree to which the potential changes have been identified during the SM process. Based on SMTH, changes could be identified (i.e., identified change) or not (i.e., latent change). In the model, tasks that flowed from 'WTD' stock to 'WACCMGD' stock are identical to identified changes (C in Figure 4). Then, these identified changes can be approved (i.e., approved change) or rejected (i.e., rejected change), based on the decision of the CCM group. The CCM group, which is includes the construction manager as well as other high-level management, plays a role in deciding whether this potential change needs to be approved or not. In the model, if a change is rejected, tasks that have been suspended would flow back to 'WTD' and will be performed (D in Figure 4). If a change is approved, tasks would also flow back to 'WTD', however, in this case, with additional work generated by this approved change (E in Figure 4).

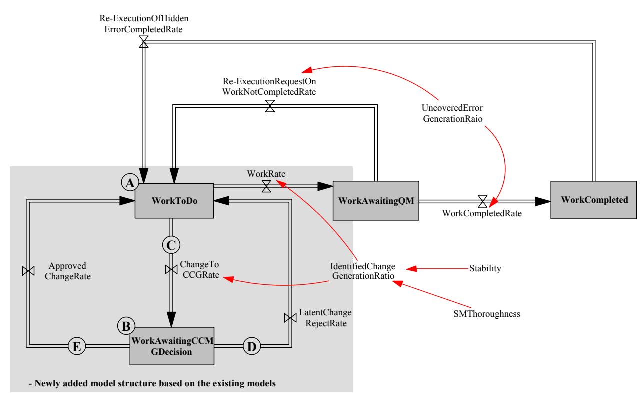


Figure 4: Change Management Model

Like this example, the generic process model represents the design and construction process with errors and changes and further, captures their impacts on work scope, which ultimately, relates to construction performance. The detailed model structure can be found in (Lee 2003).

3.3 Supporting Model Structure

Based on the generic process model, the other supporting model structures are implemented. For example, Figure 5 simulates the process of adjusting the current workweek (i.e., work hours per week) is implemented to a desired workweek level by adopting an overtime policy. First, a required work rate is calculated by dividing the remaining work by available time to completion. Then, the schedule pressure is determined by comparing the calculated required work rate against the normal work rate. In the model, when the required work rate is greater than the normal work rate, it is assumed that contractors and project managers perceive the schedule pressure with a time delay. Based on the perceived schedule pressure, the overtime ratio and workweek are determined. Here, the overtime ratio ranges from 1.0 to 2.0, which means that construction workers can work up to 80 hours per week due to the degree of the schedule pressure, if we assume a normal workweek is 40 hours per week (considering that the overtime ratio can vary depending on construction conditions and policies, the model can have a different overtime ratio range based on a user's choice). This overtime ratio is used to calculate a actual workweek and consequently, the gap between a actual workweek and a normal workweek can be used to calculate the fatigue of the workforce, which will result in productivity loss.

In summary, these supporting model structures are designed to represent the diverse construction policies with their softer aspects, which basically are generated from introduction of errors and changes.

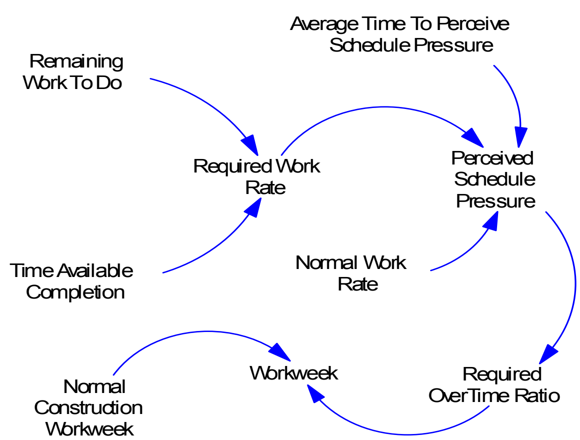
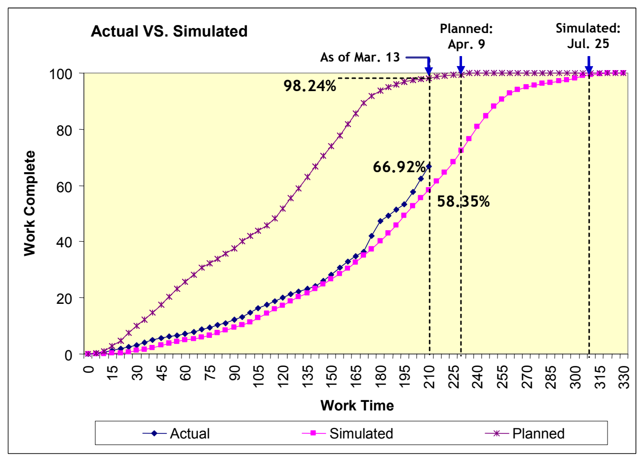


Figure 5: Example of Supporting Model Structure

4 VALIDATION

The model has been validated in terms of its usefulness in identifying the impacts of errors and changes on design and construction performance. For example, direct structure tests were conducted with the industrial partners: InteCap Inc., Modern Continental, and Barletta Heavy Division, in order to confirm that the developed model structure correctly represents the quality and change management process. In addition, in terms of the behavioral aspect, behavior reproduction tests, were conducted by confirming whether the simulation results would produce the same behavior observed in the actual case. Figure 6 shows the simulation result in one of the case studies, which the author conducted in Malaysia (for confidentiality reasons, the project name is not stated). As of March 13, the actual Percentage of Work Complete (PWC) is far behind the planned PWC due to delay caused by errors and changes. However, the simulated PWC from our model is almost following the actual PWC with 3.38% of Root Mean Square Error, which can be acceptable in terms of the model accuracy. Furthermore, this statistical error (i.e., the gap between the actual and the simulated) does not have to be considered as 'model error' because it can explain other impacts such as the variables that were not modeled or the impacts of hidden errors and latent changes (i.e., recall the one of the aforesaid arguments that the monitored performance may not catch the real performance).



N	R^2 (%)	Root Mean Square Error (%)
43	99.5	3.38

Figure 6: Model Testing Example – Case Project in Malaysia

5 CASE STUDY

The developed model was applied to a real-world design and construction project in order to examine its applicability. The Treble Cove Road bridge project, which is a part of roadway improvements along State Route 3 in Massachusetts, is introduces as the case study project for this paper. It was awarded to Modern Continental Companies, Inc. as a Design/Build project. The total estimated project cost was four hundred million US $ and the duration was estimated to have a 42 month span from design to construction. The case project is one of total 27 bridge projects and is composed of 28 design and construction activities.

5.1 Base Run

Simulation was performed focusing on how errors and changes affect project performance when the currently outstanding policies of this case project and its estimated characteristics are applied. For example, overtime is applied, and a Request For Information (RFI) period (time to be taken to get the reply through the RFI process) and Claim and Change Management (CCM) period (time to be taken to get the decision through the CCM process) were determined to be 7 days and 10 days, respectively, for this case project. This case is denoted as the base case hereinafter and is compared to the Critical Path Method (CPM) estimation.

The simulated duration of the base case is 537 working days, which is much longer than the CPM duration, 381 days. This is because CPM does not consider the impacts of errors and changes on construction performance, particularly, because of an additional work scope which was not considered at the planning stage. In the six month review, it turned out that the case project was delayed in the same manner as the base case simulation had produced.

In more detail, the final design activity of the case project has a finish-to-start (FS) relationship with the shop drawing submittal activity. The subsequent construction activities follow the design activities, as seen in Figure 7. In the base run, many errors and changes were generated during the final design, which consequently, became “bottlenecked”, delaying the project’s progress. As a result, a large coordinating work amount was observed, caused by waiting for a RFI reply and the CCM decision. (Column A in Figure 7).

In addition, a significant work amount was newly introduced to deal with errors and changes in the final design (Column B in Figure 7) and also contributed to delay. Furthermore, a large fraction of errors and changes were not identified and became hidden errors and latent changes (Column C in Figure 7). This situation also required much effort in coordinating with the predecessor activity through RFIs. In reality, it turned out that the design work was forced to proceed without the establishment of a detailed work scope by the owner. Therefore, requests for design clarification and design changes were frequently made by the contractor, and design omissions and errors were committed by the design group of the team.

In addition, the shop drawing review and the corresponding fabrication were developed concurrently with start-to-start (SS) relationship with a lag of 5, as seen in Figure 8. However, significant number of hidden errors and latent changes were generated at the final design stage and consequently, deteriorated construction performance. At that time, a significant amount of additional work was introduced with the fabrication activities (A in Figure 8) because the final design, the source that introduced the original errors and changes (C in Figure 7), had already been completed.

This situation can generate a very serious impact on performance such as generating ‘a derivative activity’, which calls for the re-execution of already withdrawn activities (Lee et al. 2003b). However, it did not happen in the actual execution, mainly due to the fact that the contract was a design-build contract (a single contract between owner and design-builder and thus, design and construction are performed by one team). In other words, a design team could work continuously to correct their designs without causing any additional cost, contract, or liability issues.

However, many coordination issues between the design and construction phase surfaced and consequently, contributed to the delay in the RFI and CCM process. Actually, the model highlighted the fact that the design-build team did not have much experience in working together as part of this type of team. (This project was their first design-build contract in which these two groups worked together).

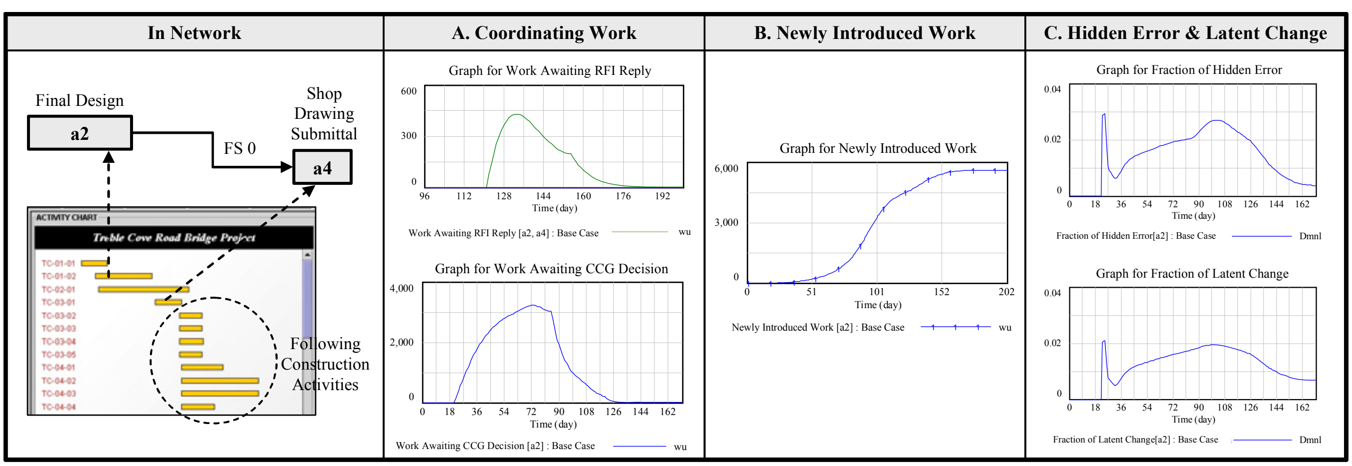


Figure 7: Impact of Errors and Changes

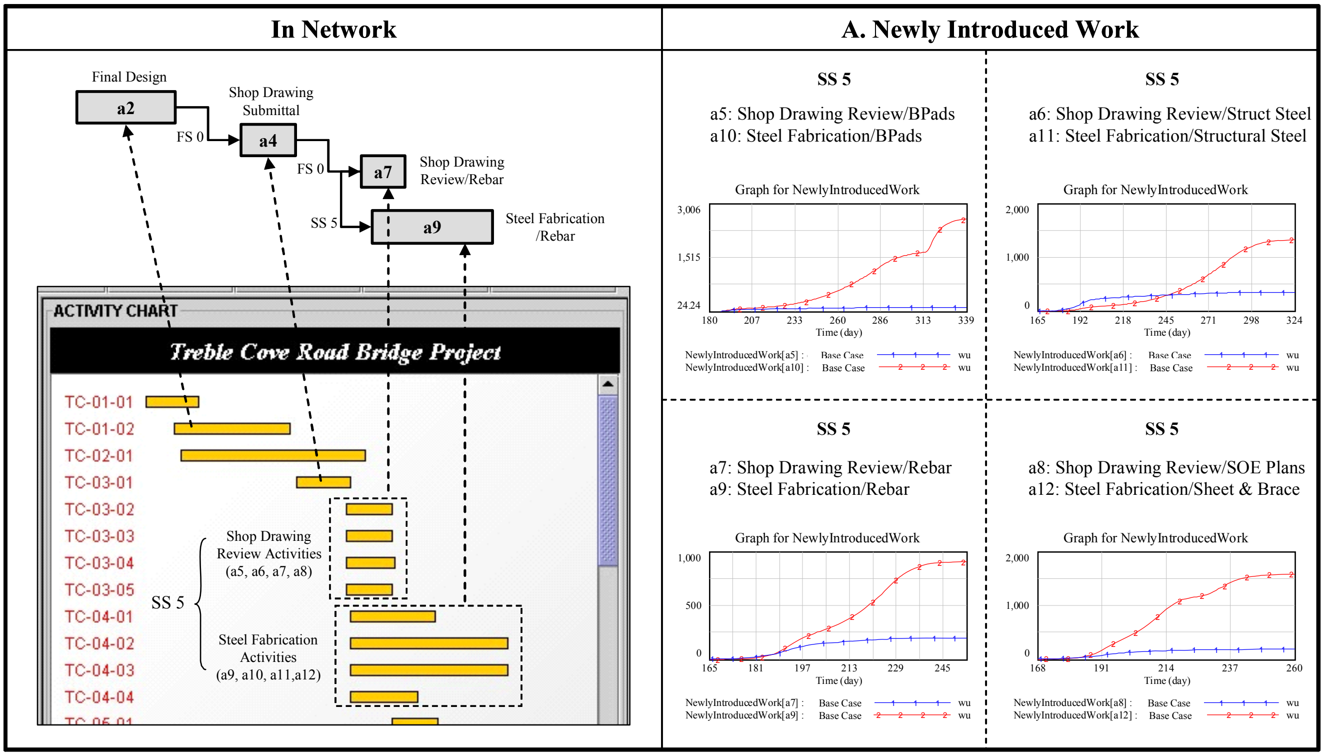


Figure 8: Impact of Preceding Errors and Changes on Succeeding Construction Activities

5.2 Policy Recommendations

Based on the diverse simulation analysis, the following policy recommendations were made to improve the case project's performance.

First, implementing an efficient coordination process is recommended. As discussed earlier, the case project is not able to assist in the generating many errors and changes by nature, because the owner forces design work to proceed before establishment of a detailed work scope. If this is a reality, (issues with the owner are beyond this research's scope) the next best policy could be to improve the coordination process for errors and changes. In addition, the lack of the experience of working together as design-build team makes this project more difficult to coordinate the settlement of errors and changes through the RFI and CCM process. Simulation results shows that increasing the level of coordination among project functions (i.e., reducing RFI period and CCM period) could contribute to reduce the project completion time. For example, when a reduced RFI and CCM period (7 → 4 days and 10 → 6 days, respectively) were used, the project completion time was reduced from 537 to 511 days.

Another point to improve project performance is developing a mechanism that identifies hidden errors and latent changes as early as possible. A collaborative meeting with the design group and involved project functions before an activity starts could be one example. This meeting can be designed to share and discuss potential problems, such as clarifying the ill-defined tasks (e.g., designs), making sure of the accuracy and constructability of drawings and securing resource procurement. By implementing these meetings, there would be more chances that hidden errors and latent changes can be identified, due to their collaborative efforts to reduce potential problems in advance. Further, it could also reduce the number of RFIs which often create a bottleneck, due to its sudden overflow. The simulation result that applied this 'meeting process', together with reduction of RFI and CCM period, was estimated as 486 days because the collaborative meeting allows for more efforts to discover potential problems including hidden errors and latent changes.

Lastly, a flexible head count control policy (workforce can be hired whenever required during actual execution) can be more effective in dealing with the sudden work overflow caused by errors and changes than the typical overtime, which is widely used in construction. The simulation result with a flexible headcount policy, shows that the project completion time could be reduced to 461 days, together with applying the reduction of a RFI and CCM period and the collaborative meeting, by assigning the workforce in a timely manner.

6 CONCLUSION

In the area of construction simulation,, Discrete Event Simulation (DES) has been widely adopted and has proven its capability to represent detailed construction operations.

However, in terms of policy making to improve the whole system performance (i.e., strategic simulation), System Dynamics (SD) could be used as a complementary tool to DES by providing the mechanism to understand system structure (e.g., feedback processes). Applying SD into error and change management in concurrent design and construction, this paper concludes that SD can provide a great advantage to the understanding of a complex system and, suggest which appropriate policies would apt to improve system performance.

Although the current SD model has established the potential for error and change management in concurrent design and construction, further research efforts need to be made to improve its detail representation of the different construction situations. A hybrid modeling approach which combines SD with DES is being considered. By doing this, whatever the interest or the focus may be, the model could flexibly represent the overall system behavior as well as the detailed operational detail.

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