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MODELING AND REPRESENTATION OF NON-VALUE ADDING ACTIVITIES DUE TO ERRORS AND CHANGES IN DESIGN AND CONSTRUCTION PROJECTS

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ABSTRACT

Non-value adding activities which consume time and/or resources without increasing value, have been considered as main contributors to schedule delays and cost overruns in design and construction projects. While these activities are mainly triggered and proliferated by errors and changes, traditional construction management approaches have not explicitly addressed the impact of errors and changes on non-value adding activities. To capture non-value adding activities due to errors and changes, a system dynamics based simulation model is developed and presented in this paper wherein the impact of non-value adding activities are intuitively visualized in a colored bar chart. The developed model is applied to a bridge project in Massachusetts. The simulation results show that errors and changes resulted in 26.1% of non-value adding activities and 171 days of schedule delays in this project. Based on these simulation results, it is concluded that the developed simulation model holds significant potential to aid better decision-making for controlling non-value adding activities in design and construction projects.

1 INTRODUCTION

Despite advances in construction equipment and management techniques, schedule delays and cost overruns chronically persist in design and construction projects (Park and Peña-Mora 2003). As a main contributor to schedule delays and cost overruns, a number of previous research efforts have pointed to 'non-value adding activities' which consume time and/or resource without increasing value (Koskela 1992). For example, Ireland (1995) revealed that the amount of non-value adding activities can be as high as 40% of the overall project time. Similarly, Jergeas et al. (2002) reported that 40-60% of a typical construction day is wasted on non-productive activities. Recently, Horman and Kenley (2005) concluded that an average of 49.6% of operational efforts are devoted to non-value adding activities. Such findings support an argument that successful execution of design and construction projects is directly related to management's efficiency in minimizing non-value adding activities.

2 NON-VALUE ADDING ACTIVITIES IN DESIGN AND CONSTRUCTION PROJECTS

Based on their ability to generate project value, construction activities can be subdivided into value adding activities, value supporting activities and non-value adding activities.

Value adding activities (VAAs) are operational efforts which realize project requirements defined by contract. For example, concrete pouring can be considered a VAA as it transforms concrete into a building component like a retaining wall. VAAs are explicitly identified in construction plans and recognized as indispensable elements, based on which construction managers estimate required project duration and cost. In light of this recognition, construction industry has traditionally striven to achieve schedule reduction and cost savings by improving efficiency of these activities.

Value supporting activities (VSAs) are supportive efforts that do not directly add value, however they indirectly support other VAAs. An example of VSAs is inspection of building components which prevents propagation of problems (e.g., construction error) to subsequent activities. VSAs are also explicitly recognized but often regarded as activities that also should be minimized for better project performance as they do not directly add value to the project.

Non-value adding activities (NVAAs) are wasted efforts that consume time and/or resources but do not directly or indirectly add value or progress to the project requirements (Koskela 1992). In other words, NVAAs can be defined as wasted consumption of time and/or resources in a project that could have been avoided if the project was more carefully planned, executed, monitored and controlled. An example would include erroneous execution of a building component leading to rework.

One thing to note is that all three activity types (VAAs, VSAs and NVAAs) consume time and/or resources regardless of adding value, i.e., total amount of efforts required for a project is a sum of amount of effort required for VAAs, VSAs and NVAAs. As NVAAs does not add any value, lesser the amount of NVAAs included in a project, better will be the performance of the project. This is the main reason why construction managers should pay attention to minimize NVAAs while executing their projects.

Despite the significance of managing NVAAs, critical path method (CPM), the most widely utilized formal scheduling technique in the A/E/C industry (Senior and Halpin 1988), is known to be ineffective in identifying and controlling these activities. The reason being that CPM does not differentiate VAAs and NVAAs (Lee et al. 1999). In order to address this issue, the A/E/C industry has added adjustments to the CPM approach. For example, the A/E/C industry applied contingency to the CPM approach based on past experience on similar projects or used three duration factors (optimistic, most likely and pessimistic durations) in the PERT approach. As more advanced methodologies have become available, the A/E/C industry also applied stochastic sampling techniques such as Monte Carlo Simulation or Latin Hyper-Cube method to the CPM approach so that it could incorporate detrimental impact of NVAAs. While these modifications are all meaningful and may address the impact of NVAAs in an implicit manner, they often hamper the analysis of the dynamics of NVAAs to find an effective way of preventing their detrimental impact.

In order to explicitly address NVAAs, a series of construction process analysis techniques (Oglesby et al. 1989) has been extensively adopted in the A/E/C industry. While these techniques are known to be very effective at discovering and eliminating unnecessary operations in a repetitive construction process, these are not particularly supportive to specifically identify and quantify NVAAs triggered by errors and changes (Lee et al. 1999). However, understanding that it is almost impossible to expect a perfect execution environment where no errors and changes exist, current planning and control methods need to be augmented to fully understand and manage NVAAs in design and construction projects. As an effort to address this necessity, this paper suggests a system dynamics simulation based approach which enables modeling and representation of NVAAs triggered by errors and changes.

3 MODELING NON-VALUE ADDING ACTIVITIES IN DESIGN AND CONSTRUCTION PROJECTS

3.1 Conceptual Model

Construction production system is modeled using System Dynamics (SD) modeling approach in this paper. This model was originally developed by Cooper (1990), evolved by Ford and Sterman (1998) and expanded by Park and Peña-Mora (2003) and Lee et al. (2005). By applying analogies from hydraulics on how water flows from one tank to the other, these models basically interpret project management as a progression of transferring work items in a tank (generally called 'Work To Do') to another tank (called 'Work Done'). Based on this idea, in order to explicitly identify and quantify NVAAs due to errors and changes, this paper focuses on the amount of efforts that is actually utilized to add value. For this purpose, construction production system is interpreted as conversion of *Assigned Efforts* to *Value Added Efforts,* thereby generating project value.

In an ideal construction production system, where there exist no NVAAs, it is assumed that the assigned efforts would be thoroughly utilized to add value and the value would be added in a linear fashion. Contrary to these assumptions of the ideal construction production system, in real project management, errors and changes may exist, which often introduce NVAAs to the construction production system. Errors and changes generally trigger NVAAs in the forms of *interruption*, *productivity loss* and *rework*. For example, errors and changes may interrupt a process by creating execution environments quite different from the expected ones. Also, errors and changes can significantly decrease productivity and the process may require additional time and efforts. Finally, errors and changes may introduce rework accompanied by the request of additional time and efforts. While their occurrence patterns and timings are quite different, these (*interruption*, *productivity loss* and *rework*) have a common feature in that they all generate wasted efforts (i.e. NVAAs) and consequently require additional time and efforts in order to compensate the wasted efforts. Such additional time and efforts are the direct cause of schedule delays and cost overruns in design and construction projects.

3.2 Measuring Non-Value Adding Activities in Design and Construction Projects

As previously mentioned, the amount of NVAAs in an activity can be measured by the total efforts wasted due to *interruptions*, *productivity loss* and *rework*. In order to mathematically formulate this, this paper proposes a metric called 'Value Addition Rate (VAR)' which captures the amount of NVAAs in a given activity at a given time.

$$VAR_i(t) = 1 - \frac{WI_i(t) + WP_i(t) + WR_i(t)}{AE_i(t)},$$

Where i = given activity,
t = given time,
WI = wasted efforts due to interruption,
WP = wasted efforts due to productivity loss,
WR = wasted efforts due to rework,
AE = assigned efforts.

Assume that 25 units of 'aluminum windows', each of which requires 4 labor-hours are ready to be installed and 100 labor-hours are initially assigned for this activity. In this case, if 10% of the assigned efforts are wasted by *interruption*, another 10% by *productivity loss* and the other 10% by *rework*, only 72.9 labor-hours (100*0.9*0.9*0.9) of the assigned efforts would be utilized to add value. Therefore, in this case, the VAR would be 72.9% and this implies 27.1% of the assigned efforts would be wasted due to NVAAs. Consequently, only 18 units of the windows would be installed with the initially assigned efforts and additional time and efforts would be required to install the remaining 7 units, leading to lowered schedule and cost performance. As shown in this example, the VAR metric captures combined effect of *interruption*, *productivity loss* and *rework* on value stream of construction production system. Using this metric, the robustness of construction production system against negative impact of NVAAs is assessed in the following sections.

3.3 Feedback Mechanism Model

One challenging issue in measuring the impact of NVAAs, is that the amount of NVAAs can vary by process feedback mechanism. In order to closely examine interrelationship between NVAAs and errors and changes, a *causal-loop diagram* is developed, which is usually implemented in system dynamics approaches to visualize how interrelated variables affect one another (See Figure 1).

As previously mentioned, the total amount of efforts is the summation of VAAs, VSAs and NVAAs (Figure 1, A, B and C). Once errors are found through quality management process, these may need to be reworked, which ultimately increase the amount of NVAAs (Figure 1, D and E). Also, since rework is usually accompanied by the demolition of what has already been built, construction managers tend to avoid rework on problematic activities by modifying their design and specification (Park and Peña-Mora 2003, Figure 1, F). In addition to the quality issues, design change issues can often arise due to different site conditions or owner's preference. In such a case, RFI would be sent to the design team and the process could be interrupted until the requested information arrives, which also generate NVAAs (Figure 1, G and H).

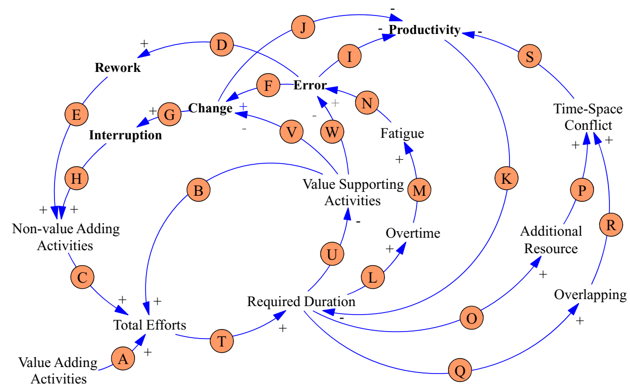

Figure 1: Feedback Mechanism Model

In addition to *rework* and *interruption*, errors and changes can often result in *productivity loss* (Halligan et al. 1994). If a process is executed with lower productivity than planned one, the process would require longer duration and more resources than initially planned, which are the direct causes of schedule delays and cost overruns (Figure 1, I, J and K). In order to prevent these, a construction manager typically tries to adopt control actions to keep the process back on the track. For example, overtime policy is often adopted, as it can result in a higher rate of progress without any coordination problems and any additional craftspersons (Hanna et al. 2005). However, overtime policy may introduce additional problems such as fatigue which can ultimately bring in more errors and productivity loss (Figure 1, L, M and N). In addition to overtime policy, assigning additional resources or overlapping is also widely adopted for schedule acceleration. While these strategies do not trigger fatigue, they usually result in site congestion and time-space conflicts which can significantly deteriorate productivity (Akinci et al. 2002) (Figure 1, O, P, Q, R and S). Also, in order to shrink the total duration, the construction manager may assign less efforts for VSAs (e.g., prechecking or inspection) since these activities are explicitly addressed but do not add any value. By doing this, the construction manager can temporarily decrease total efforts and consequently reduce the process duration (Figure 1, B, T and U). However, this may hamper timely detection of errors and changes, which can result in further detrimental effects on the process (Figure 1, V and W). The reason is that the longer it takes to identify errors and changes, more serious is the potential damage and more complex and costly corrective actions will likely be necessary (Navon and Goldschmidt 2003).

Based on all these explanations, it could be well understood that the amount of NVAAs can become dramatically compounded by its interaction with errors and changes. While this feedback mechanism is crucial to quantify the amount of NVAAs, the traditional approaches lack capability to deal with this mechanism.

3.4 Simulation Model

Based on the conceptual model and feedback model explained above, a simulation model is developed using AnyLogic 6 (XJ technologies 2007). For detailed quantification, the Dynamic Planning and Control Methodology (Lee et al. 2005), which has been credited for its effective modeling of quality and change management process in design and construction projects, is adopted as backbone for this model. For representing interactions among interrelated processes, the model is developed using object-oriented concept and has two distinct layers: *project* and *activity*. A project layer has a number of activities and deals with their interactions depending on imposed precedence relationships and provides project level information (e.g., total project duration). On the other hand, each activity layer quantifies the amount of NVAAs (i.e., *interruptions*, *productivity loss* and *rework*) using about 80 variables and 110 functions. While the simulation model is not specifically explained due to limited space, interested readers can find detailed information in Lee et al. (2005).

In order to test the validity of the simulation model, a single construction activity is simulated and the results are examined to find the amount of assigned efforts that is actually utilized to add value (VAR metric). For this simulation, assuming no NVAAs exist, the initial duration is considered to be 60 days and 20% of errors and changes are initially expected. Figure 2 shows that only 60% of the assigned efforts are utilized to add value and the other 40% of the efforts are wasted at the early stages (Figure 2, A). Possible reasons for this low VAR are *interruptions* due to frequent RFIs resulting from changes and *productivity loss* due to labors' unfamiliarity with construction plans. As time goes on, more efforts are devoted to generate value and gradually the VAR metric reaches 95% around 60 hours (Figure 2, B). This implies that increased learning effects and schedule pressure decrease *productivity loss* and increase the VAR. However, at later stages, the VAR drastically drops due to late discovered errors (Figure 2, C). These simulation results show that a significant amount of the efforts may be wasted in accommodating changes and rectifying errors if the errors and changes are not promptly identified and resolved.

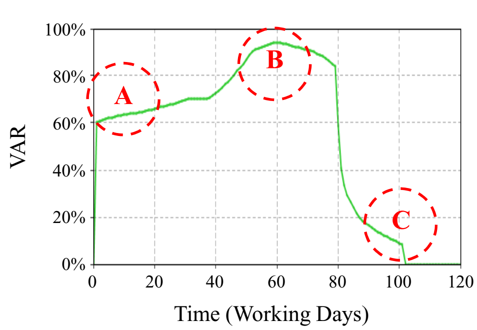

Figure 2: VAR in a Behavior Graph

4 REPRESENTATION OF NON-VALUE ADDING ACTIVITIES IN DESING AND CONSTRUCTION PROJECTS

In the preceding section, we introduced a simulation model and the simulation results showed that NVAAs can significantly affect performance of design and construction projects. Represented in a behavior graph like Figure 2, the simulation results can be helpful to address potential problem areas in an activity and prepare management plans for the expected problems. However, from a project level where a number of activities need to be considered together, it can be difficult to quickly grasp the implication of simulation results using a behavior graph. In order to identify problematic areas in certain activities from a higher level in a more intuitive way, more efficient representation is required.

4.1 Limitation of Current Methods in Representing Non-Value Adding Activities

Current scheduling methods can be subdivided into *time-scaled methods* and *non-time-scaled methods* depending on whether the lengths of the constituting activities follow a time-scale (Francis and Miresco 2006). In *non-time-scaled methods* like CPM, problematic areas in an activity (as shown in Figure 2) cannot be easily identified since the length of boxes used in the precedence diagram method (PDM) or the length of the arrows used in the arrow diagram method (ADM) is not proportional to the duration of the activity (McGough 1982). In this context, *time-scaled methods* like a Gantt chart can be more suitable to represent problematic areas in an activity. However, a Gantt chart's current monotone representation format only provides overall information of an activity and could not show how much efforts were actually utilized to add value (i.e., the VAR metric). For example, if a delayed schedule due to NVAAs was recovered by adopting overtime policy and/or assigning more workers, the problematic areas would not be visible anymore. In order to address this issue, a colored bar chart is proposed in the following section.

4.2 A Colored Bar Chart Approach

Using different color schemes, the percentage of efforts effectively utilized to add value (VAR) can be represented in a bar chart. For colored representation, we use 4 color zones (Green, Yellow, Orange and Red) depending on the proportion of efforts effectively utilized.

- Green Zone: $0.9 < \text{VAR}$
- Yellow Zone: $0.7 < \text{VAR} \leq 0.9$
- Orange Zone: $0.5 < \text{VAR} \leq 0.7$
- Red Zone: $\text{VAR} \leq 0.5$

Using the above categorization, the VAR can be represented at every time step (e.g., hour, day, or week). By doing this, construction managers can intuitively identify potential problematic areas and prepare management plans for the expected problems. Figure 3 shows an example of a behavior graph (Figure 2) converted into a colored bar chart representation. As shown, Figure 3 illustrates the problematic areas and directs where managerial efforts should be.

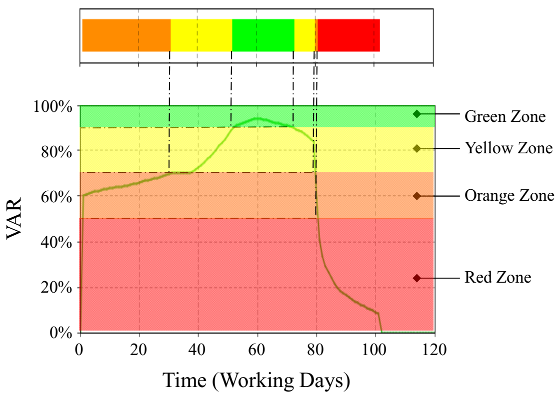

Figure 3: A Colored Bar Chart Approach

5 MODEL APPLICATION

In order to test applicability of the developed simulation model and the proposed colored bar chart approach in terms of identifying and quantifying NVAAs, a real-world design and construction project is investigated.

5.1 Case Study – A Bridge Project in MA

The Treble Cove Road bridge project in MA is selected as a case study project for this paper. This project had been cumulatively addressed by Park and Peña-Mora (2003) and Lee et al. (2005). Interested readers can find detailed simulation settings and results for this project contained therein. Based on their previous works on overall project behavior, this paper focuses on identification and quantification of NVAAs in this project.

5.2 Simulation Results

Figure 4 shows the simulation results of how errors and changes negatively affects project performance. It shows the project's 28 sub-activities ('A' and 'B' in Figure 4) and each activity's initially expected errors and changes ('C' and 'D' in Figure 4). Figure 4 also shows a Gantt-bar chart ('E' in Figure 4) comparing the initial schedule (not con-

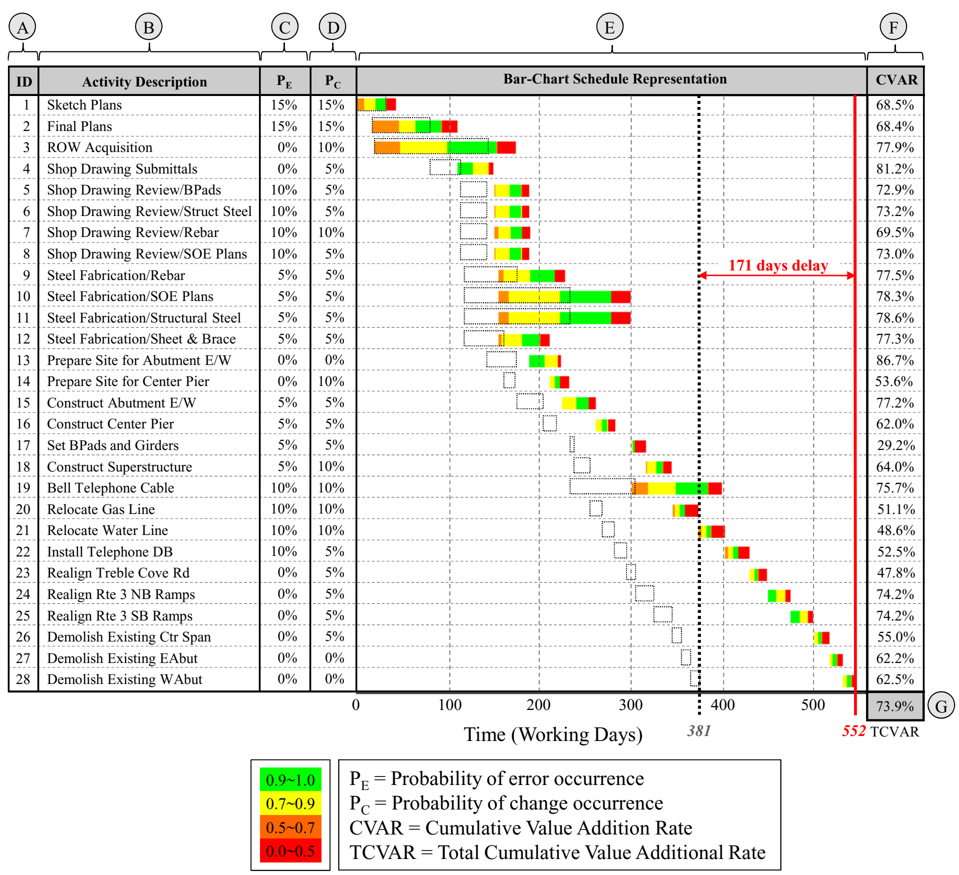

Figure 4: Simulation Results in a Colored Bar Chart

sidering impact of errors and changes) and the simulated schedule (incorporating impact of errors and changes). In Figure 4, the initial schedule of each activity is shown in dotted blank boxes and the simulated schedule information is represented in a colored bar as shown in Figure 3. When it is assumed that there would be no NVAAs due to errors and changes in this project (i.e., the initial schedule), the estimated project duration is 381 working days. However, unlike this optimistic estimation, the simulation results show that errors and changes trigger significant amount of NVAAs (26.1% of total project efforts, based on 'G' in Figure 4) causing 171 working days of delay thereby increasing total project duration to 552 working days.

Figure 4 also shows that each activity's CVAR is less than 100% meaning it faces certain amount of NVAAs. In order to closely examine this at an activity level, the 'Final Plans' activity (the 2nd activity) is further investigated. Figure 5 shows detailed simulation results on the 'Final Plans' activity. It shows that 25% of the assigned efforts are wasted by *productivity loss* and 15% of the assigned efforts are wasted by *interruption* at early stages (20-45 working days). This is due to the design team's lack of understanding of project requirements and unfrozen project scope at this moment. Getting concerned about meeting the deadline due to the wasted efforts at the early stages, the design team starts to feel schedule pressure and expedites the progress.

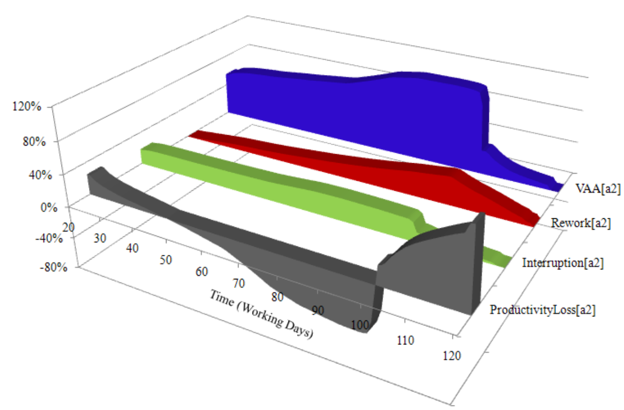

Figure 5: Non-Value Adding Activities in the 'Final Plans'

Under this schedule pressure, the design team exhibits a higher production rate than nominal one and the activity shows faster progress at mid stages (45-95 working days). However, it is notable that the amount of efforts wasted by *rework* is also increasing. This means that progress expedition at that stages generates additional problems such as design errors, omission and inconsistency. Also, the simulation results show that such a demanding environment hampers timely detection of these problems and consequently these problems are addressed and rectified at later stages (95-120 working hours). As a result, due to these late discovered problems and small amount of remaining work, significant amount of the assigned efforts is wasted by *productivity loss* at later stages.

The simulation results imply that it is important to prepare a reliable and stable execution environment before executing a design and construction activity. The reason is the wasted efforts at early stages can increase schedule pressure in the middle stages which may generate additional problems and hamper their instant discovery. In this context, while it is ideal to completely eliminate the source of NVAAs, it is almost impossible because of uncertainty and the complexity inherent in design and construction projects. Thus, the generated problems need to be identified and rectified as early as possible before their negative impact can be propagated to other related activities.

Also, the simulation results (Figure 3) show that the CVAR of some activities (the 14th, 17th, 20th, 21st, 22nd, 23rd and 26th activity) are less than 60%. Table 1 shows that initial values of key input variables (e.g., how much errors are expected and how much changes are expected) for these activities (See 'Base Case-Study' column in Table 1). While not much errors and changes are expected in these activities, their low CVAR indicates that the amount of NVAAs in an activity can also be significantly triggered by other related activities.

Table 1: Comparison of Simulation Results

Activity ID	Base Case-Study			Controlled Case-Study		
	P_E	P_C	CVAR	P_E	P_C	CVAR
14	0%	10%	53.6%	0%	0%	64.6%
17	5%	5%	29.2%	0%	0%	35.4%
20	10%	10%	51.1%	0%	0%	65.0%
21	10%	10%	48.6%	0%	0%	71.4%
22	10%	5%	52.5%	0%	0%	75.0%
23	0%	5%	47.8%	0%	0%	62.5%
26	0%	5%	55.0%	0%	0%	62.2%

P_E: Probability of error occurrence
P_C: Probability of change occurrence

In order to confirm this, the simulation scenario is modified so that no errors and changes are expected in these activities (See 'Controlled Case-Study' column in Table 1). The modified simulation results show that these activities' CVAR improves but a significant amount of NVAAs still remains and affects the performance. These simulation results demonstrate that NVAAs in an activity can be generated by other related activities even when no errors and changes are originated from the activity itself. Due to this propagational nature, NVAAs in an activity cannot be effectively eliminated by putting managerial efforts only on the problematic activities. Rather, both careful investigation of the activity itself and understanding its interactions with other related activities need to be simultaneously considered.

6 CONCLUSION

Non-value adding activities are a major reason behind schedule delays and cost overruns in design and construction projects. For this reason, to successfully execute design and construction projects, one should pay attention to minimize the amount of NVAAs. Also, in order to prepare an effective management plan for minimizing NVAAs, these activities should be first identified and quantified. To address this issue, this paper proposed a simulation based approach which enables modeling and representation of NVAAs in design and construction projects. Upon applying this approach to a bridge project, the proposed model revealed that 26.1% of the assigned efforts were wasted resulting in 171 working days of schedule delay in the case project. Also, the simulation results confirmed that NVAAs in an activity can be easily propagated to other related activities. The simulation results imply that a holistic approach is required to manage NVAAs in design and construction projects.

While the proposed model has established the potential to identify and quantify NVAAs, it needs further enhancement for finding an effective way of controlling NVAAs. To achieve this goal, the writers are investigating on how VSAs can be utilized to reduce negative impact of NVAAs and consequently increase performance of design and construction projects. Example of this case is a situation wherein potential problems are addressed and resolved before an activity starts through VSAs (e.g., pre-checking or constructability review), the activity may be executed with less *interruption*, *productivity loss* and *rework* and exhibit higher schedule and cost performance. Corresponding results will be reported in near future.

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REFERENCES

Akinci, B. Fischer, M., Levitt, R. and Carlson, R. 2002. Formalization and Automation of Time-Space Conflict Analysis. *Journal of Computing in Civil Engineering,* ASCE, Vol. 16, No. 2, pp. 124-134.

Cooper, K. 1990. Naval ship production: A claim settled and a framework built. *Interface*, Vol. 10, No. 6, pp. 20-36

Ford, D. and Sterman, J. 1998. Dynamic modeling of product development processes. *System Dynamics Review*, Vol. 14, No. 1, pp. 31-68.

Francis, A. and Miresco, E. 2006. A chronographic method for construction project planning. Canadian Journal of Civil Engineering, Vol. 33, No. 12, pp. 1547-1557.

Halligan, D.W., Demsetz, L.A., Brown, J.D. and Pace, C.B. 1994. Action-response model and loss of productivity in construction. *Journal of Construction Engineering and Management*, ASCE, Vol. 120, No. 1, pp. 47-64.

Hanna, A.S., Taylor, C.S. and Sullivan, K.T. 2005. Impact of Extended Overtime on Construction Labor Productivity. *Journal of Construction Engineering and Management*, ASCE, Vol. 131, No. 6, pp. 734-739.

Horman, M, J. and Kenley, R. 2005. Quantifying Levels of Wasted Time in Construction with Meta-Analysis. *Journal of Construction Engineering and Management*, ASCE, Vol. 131, No. 1, pp.52-61.

Ireland, V. 1995. The T40 project: process re-engineering in construction. *Australian Project Manager*, AIPM, Vol. 14, No. 5, pp. 31-37.

Jergeas, G. F., Chishty, M. S. and Leitner, M. J. 2000. Construction Productivity: A Survey of Industry Practices. *2000 AACE International Transactions*, AACE, PM.06: 01-07.

Koskela, L. 1992. Application of the New Production Philosophy to Construction. Technical Report No. 72, CIFE, Stanford University.

Lee, S., Peña-Mora, F. and Park, M. 2005. Quality and change management model for large scale concurrent design and construction projects. *Journal of Construction Engineering and Management*, ASCE, Vol. 131, No. 8, pp. 890-902.

Lee, S.H., Diekmann, J.E., Songer, A.D. and Brown, H. 1999. Identifying Waste: Application of Construction Process Analysis. In *Proceedings of the Seventh Annual Conference of the International Group for Lean Construction*, pp. 63-72.

McGough, E. H. 1982. Scheduling: effective methods and techniques. *Journal of the Construction Division*, ASCE, Vol. 108, No. 1, pp. 75-84.

Navon, R. and Goldschmidt, E. 2003. Monitoring labor inputs: automated-data-collection model and enabling technologies. *Automation in Construction*, ELSEVIER, Vol. 12, No. 2, pp. 185-199.

Oglesby, C. H., Parker, H. W. and Howell, G. A. 1989. Productivity Improvement in Construction. Mcgraw-Hill College.

Park, M. and Peña-Mora, F. 2003. Dynamic change management for construction: introducing the change cycle into model-based project management. *System Dynamics Review*, System Dynamics Society, Vol. 19, No. 3, pp.213-242.

Senior, B. and Halpin, D. 1998. Simplified simulation system for construction projects. *Journal of Construction Engineering and Management*, ASCE, Vol. 124, No. 1, pp. 72-81.

XJ technologies. 2007. AnyLogic 6. Available via <http://www.xjtek.com> [accessed Mar 22, 2007]

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