Impacts of Project Controls on Tipping Point Dynamics in Construction Projects

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Abstract: Large, complex construction projects such as nuclear power plants are subject to unique types of risks. One such unique risk is the combination of rework and increased project scope that can push a project from a behaviour mode of progress toward completion, past a tipping point, and into a behaviour mode of falling farther and farther behind. Previous research has demonstrated the potential of rework-induced tipping point dynamics to cause poor cost and schedule performance on large, complex construction projects (Taylor and Ford 2006) and the effectiveness of project design strategies in mitigating tipping point risk (Taylor and Ford 2008). Previous research has also examined three project labor control policies (overtime, workforce, and work intensity) and their impact on project performance (Lyneis and Ford 2007, Ford, Lyneis, and Taylor 2007). However, the impacts of project labor controls on tipping point dynamics have not been fully investigated. The current work uses a simulation model of a construction project to investigate the ability of project labor control actions to respond to tipping point dynamics. The model demonstrates that some well intended and reasonable project labor control actions, such as the extended use of overtime, can push a project over the tipping point to failure. Project robustness to tipping point-induced failure is analyzed with sensitivity analysis. Analysis results are then used to design effective project labor control responses to rework induced tipping point dynamics. Implications for practice and future research opportunities are discussed.

1. Introduction and Problem Description

Cost and schedule performance is critical for construction project success. However, many large, complex construction projects, such as nuclear power plants, fail to finish by their deadlines and within budget. For example, the first generation of U.S. nuclear power plant construction experienced average schedule overruns of 239% and average cost overruns of 338% (Taylor and Ford 2008). Although external forces such as scope changes make attaining project performance objectives difficult, internal project dynamics can reduce the ability of project managers to control the project and can drive a project to failure. One particularly challenging form of internal threats to project success is described using a tipping point. Sterman defines a tipping point as a threshold condition that, when crossed, shifts the dominance of the feedback loops that control a process (Sterman 2000). As used here, a tipping point is a threshold condition created by the shift of a project's dominant feedback structures that control project process. Rework, as one of the main causes of cost and schedule overrun (Friedrich, Daly and Dick, 1987), can cause tipping point conditions by increasing a project's work backlog continuously, pushing projects from a period of progress (i.e. increasing percent complete) over a tipping point to a period of declining progress (i.e. decreasing percent complete) and to eventual failure (Taylor and Ford, 2006).

Generally, the most effective way to manage tipping point risks is through project design during project's preliminary planning phase. Careful project process design can reduce or eliminate a project's vulnerability to tipping point failure by keeping project conditions far from those that define the project's tipping points. However, this is not always possible. Managers may also actively adjust projects throughout their duration in response to current and forecasted performance through the use of project controls including adjusting project budgets and the allocation of equipment and labor. Traditionally, three project labor control actions can be taken to correct project performance: (1) working overtime; (2) hiring more workers; and (3) pushing project staff to work faster. These control actions either increase the effective quantity of the workforce or increase the productivity of the existing workforce. However, negative impacts can also result from the use of these controls. Primary among these side effects are: (1) excessive overtime increases fatigue, resulting in errors and productivity loss; (2) additional workers reduce the short-term productivity and increase errors in the short-term and require an adjustment period to become experienced; (3) working under high pressure to perform (i.e. work intensity) creates continuous errors (haste makes waste), degrading project performance (Lyneis and Ford, 2007) (Figure 1). A shift of dominant feedback from balancing mechanisms that drive project progress to reinforcing mechanisms that drive projects to failure can induce tipping point dynamics by a continuously increasing errors and project backlog.

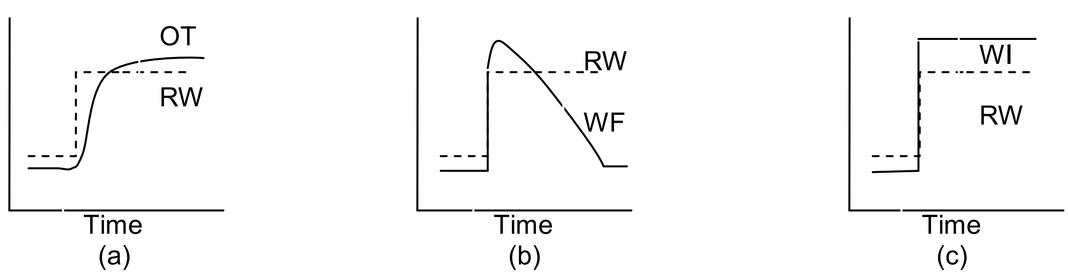
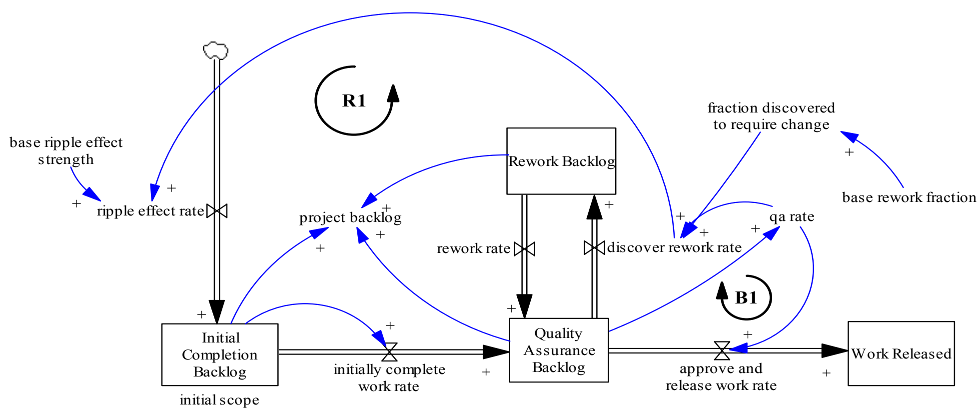


Figure 1: Impacts of overtime (OT), workforce hiring/firing or reallocation (WF), and work intensity (WI) on rework (RW) due to a step increase in the required effective workforce (based on Lyneis and Ford, 2007)

Based on rework-induced tipping point dynamics, the current work examines the response of selected project labor control policies to deviations in project performance in large, complex construction projects. The current work addresses the question, *What project labor control strategies are the most effective in managing tipping point dynamics in large, complex projects*? A simulation model of a construction project with the three traditional project labor control actions is used to explore project performance when projects are subject to tipping point dynamics. Results are analyzed for effective design of project controls to avoid tipping point risks. Conclusions are drawn and implications for future work are discussed. The previously relevant research will be reviewed next, followed by a description of the model used in the current work.

2. Background

Repenning (2001) and Black and Repenning (2001) studied tipping points in a continuous stream of development projects. Taylor and Ford (2006) demonstrated tipping point dynamics induced by rework can cause poor schedule and cost performance in single construction projects. This work introduced a dynamic project model (Figure 2) of tipping point dynamics. In the model, tipping point dynamics are described using two main feedback loops-loop B1 (Project Progress) and loop R1 (Add New Tasks). Dominance by balancing loop B1 drives the project to completion as the project backlog declines to zero; whereas continuously increasing rework and project backlog lead to project failure when reinforcing loop R1 dominates. Actual data of the Tennessee Valley Authority (TVA) Watts Bar unit 2 project was used to validate this model (Taylor and Ford 2006). In addition, this work applied sensitivity analysis to examine project robustness to tipping point-induced failure and identified project complexity ("base rework fraction", Figure 2) and the degree of project system interconnectedness ("base ripple effect strength" Figure 2) as high leverage parameters. Taylor and Ford (2008) tested the effectiveness of project design and planning strategies in mitigating tipping point risk in the Limerick Unit 2 nuclear power plant construction project.



Feedback Loop Legend:
B1- Project Progress (withdrawing work from rework cycle)
R1- Add New Tasks (adding to the total work required to complete the project through increases in the discovery of rework and ripple effects)

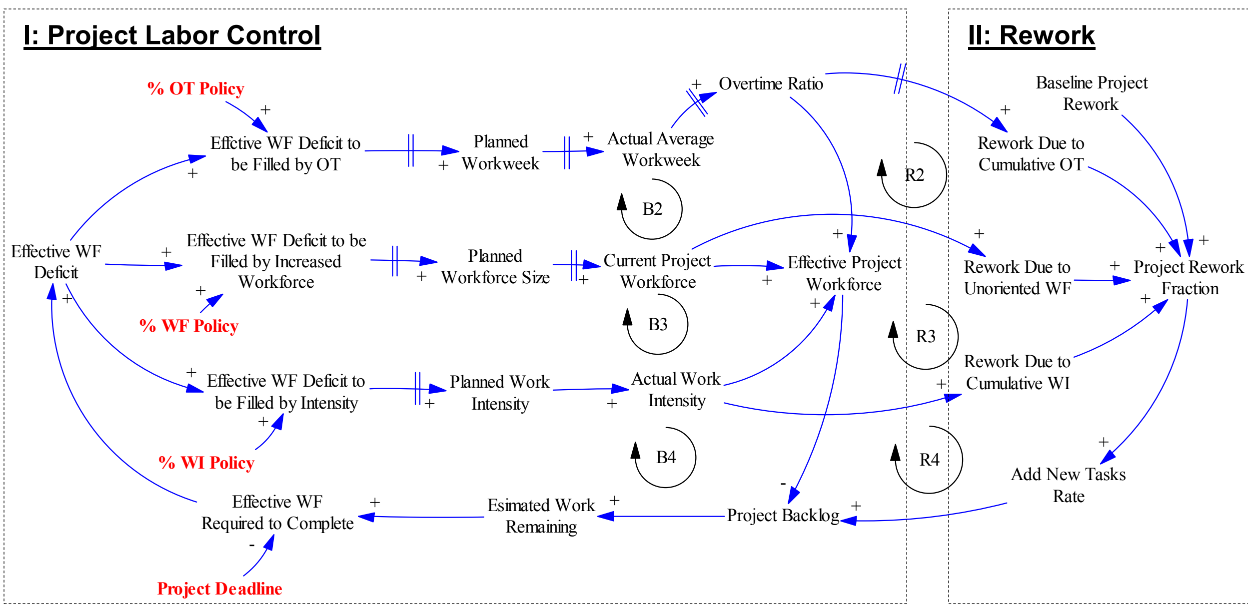
Figure 2: Conceptual project model with a tipping point structure (based on Taylor and Ford 2008)

Previous research has also examined the use of project labor controls in addressing project performance deviations. Lundgren and Schneider (1971) pointed out that hiring new people, working overtime, or doing both were often used by project manager to enable effective processing of scheduled work. The negative feedbacks caused by prolonged overtime (Hanna, Taylor, and Sullivan 2005, Thomas and Raynar 1997, CII 1988), inexperienced new staff (Eden et al 2000, Wang, Goodrum, Haas, and Glover 2008), and high work intensity (Abdel-Hamid 1984, Oliva and Sterman 2001) were considered for project controls. Dynamic feedback structures of these labor control policies have been identified (Lyneis and Ford 2007, Ford, Lyneis, and Taylor 2007).

This previous research demonstrates how tipping point dynamics can affect project performance and how project managers can design project controls (e.g. working overtime, hire/fire, work intensity, and deadline adjustment) to address project performance deviations. However, the impact of project labor control policies on tipping point dynamics has not been fully investigated. The current work addresses this knowledge gap by examining how project performance is impacted by the interaction of project labor controls and tipping point dynamics.

3. Model Structure

The model used in the current work combines the tipping point project structure of the Taylor and Ford (2006, 2008) model with the project labor control structure of the Lyneis and Ford (2007). The model consists of seven sectors: project labor controls, work flow (Figure 2), resource allocation, deadline, work forecasting, resource cost, and work progress and effort. The project labor control sector simulates labor control decisions and actions as they are driven by project schedule. Figure 3 presents conceptual cause and effect relationships map of the project labor controls sector. The current work focuses on the negative rework impacts that can be caused by the use of the project labor controls. However, these labor controls can also have significant negative impacts on worker productivity. See Lyneis and Ford (2007) and Ford et al. (2007) for more details



Feedback Loop Legend:
B2- Project management by overtime policy loop
R2- Cumulative overtime impacts on rework and project scope loop
B3- Project management by hire/fire policy loop
R3- Increased unoriented workforce impacts on rework and project scope loop
B4- Project management by intensity policy loop
R4- Cumulative work intensity impacts on rework and project scope loop

Figure 3: Conceptual causal relationships of project labor controls sector

Generally, the project labor controls sector consists of two parts-project labor control and rework. “Project labor control” reflects the application of labor control policies. “Effective WF Required to Complete” is the combined labor resources provided by a given workforce, overtime, and work intensity. This resource need is used as a criteria by project managers to decide what (if any) labor control actions are needed based on the work remaining and the project deadline. Effective workforce, measured in equivalent persons, is the product of current project workforce, overtime ratio (assuming a standard 40 hour workweek), and the current level of work intensity (with a reference work intensity value of 1). When the “Effective WF Required to Complete” exceeds the current size of project workforce, the project cannot be completed with the current workforce by the planned deadline and the effective workforce size must be increased. The model decides how much of the “Effective Workforce Deficit” will be filled by each labor control based on the user defined desired amounts using “% OT Policy”, “% WF Policy”, and “% WI Policy.” Once project labor control policies are determined, resources (i.e. workweek, workforce, and intensity) are correspondingly allocated until the completion requirements are satisfied. This process forms three balancing loops-B2 “Project management by overtime policy loop”, B3 “Project management by hirefire policy loop”, and B4 “Project management by work intensity policy loop” (Figure 3). Dominance by these balancing loops can help the project avoid tipping point risks and succeed by diminishing project backlog continuously. The model uses project labor control application delays to reflect the dynamic differences between overtime, intensity, and workforce policies (Figure 1)

However, the rework impacts of the three labor controls can defeat efforts to improve project performance. The “rework” portion of Figure 3 shows the negative impacts realized by the application of overtime, workforce, and intensity policies. In addition to the base project rework fraction, the application of overtime, workforce, and intensity policies introduce incremental errors and add new tasks that increase project scope. Three corresponding feedback loops are formed. For the overtime policy, occasional, brief overtime use as an emergency measure to address an immediate problem or opportunity can have a moderate positive effect on the effective workforce, whereas prolonged overtime working can adversely affect construction performance (Hanna, Taylor, and Sullivan 2005, CII 1988, Thomas & Raynar 1997). As the feedback loop R2 “Cumulative OT impacts on rework and project scope loop” (Figure 3) shows, continuous overtime induces fatigue and errors, resulting in additional tasks and a loss of productivity. For the workforce policy, adding new workers to the existing staff (especially by short-term hiring) can cause dilution of the average experience and learning curve effects, leading to incremental errors and rework (Eden et al 2000, Wang, Goodrum, Haas, and Glover 2008). Feedback loop R3 “Increased unoriented workforce impacts on rework and project scope loop” (Figure 3) illustrates the side effects caused by the lack of knowledge and experience of new workers. For the work intensity policy, pushing workers to perform faster inadvertently cause workers to create more errors (Abdel-Hamid 1984, Oliva and Sterman 2001). As shown in the reinforcing loop R4 “Cumulative work intensity impacts on rework and project scope loop” (Figure 3), an increase in work intensity will increase rework and project scope, and impair the project performance directly. If these reinforcing loops dominate the project moves past the tipping point into a period of continuously declining project performance and eventually to failure. The labor control policies are described with parameters that can reflect project characteristics and project manager mental processes. These parameters and their values for each labor control policy are listed in Table 1.

Additional assumptions of the project labor control model include (Ford, Lyneis, and Taylor, 2007): (1) “expert project manager” assumption (manager immediately recognizes changes in rework, scope changes, project progress, accurately forecasting resource needs, accurately measuring error fractions, etc.); (2) project labor controls cannot be reduced below their initial values; (3) project deadline is fixed.

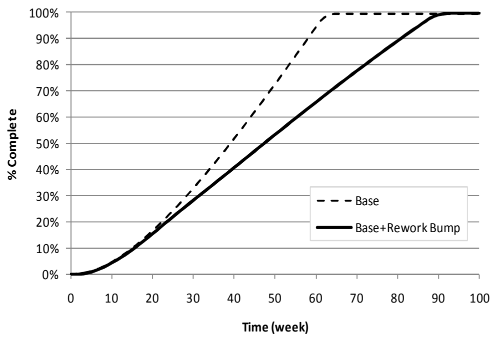
Table 1: Project labor control policy parameters and their base case values parameters

Project Controls	Parameters	Base Case Values	Units
OT Policy	% OT Policy	0~1*	dmnl
	Standard workweek	40	weeks
	Maximum workweek	80	weeks
	Planning adjustment time	1	week
	Overtime application delay	2	weeks
	Fraction of additional work due to OT that requires rework	0.1	dmnl
	OT adaption time	6	weeks
	Time to increase OT impact on rework fraction and productivity	1	week
	Average time to overcome OT rework fraction and productivity impacts	4	weeks
WF Policy	% WF Policy	0~1*	dmnl
	Planning adjustment time	1	week
	WF application delay	6	weeks
	Fraction of correct work fraction lost due to unoriented WF	1	dmnl
	WF orientation time	6	weeks
	Relative productivity of unoriented WF	0	dmnl
WI Policy	% WI Policy	0~1*	dmnl
	Initial WI	1	dmnl
	Maximum work intensity	2	dmnl
	Planning adjustment time	1	week
	Intensity application delay	1	week
	Fraction of additional work due to WI that requires rework	0.2	dmnl
	Time to increase WI impact on rework fraction	1	week
	Average time to overcome WI rework fraction impacts	4	week

*The variable is either 0 or 1 depending on project management strategies.

4. Model Behaviour and Testing

The reference case project for this work has a total scope of 500 tasks and a workforce size of 20 people. The baseline rework fraction for the project is 20%. The initial deadline of this project is 65 weeks. The model was tested using standard methods for system dynamics models (Sterman, 2000). The model's behavior for typical conditions is consistent with previous project models and practice (e.g. the "S" shaped growth of percent complete over time shown in Figure 4 "base"). The base case project is completed at week 65 for a total cost of $1.29 million[i] without using any of project labor controls. Therefore, the base case project requires rework but has enough time and resources to complete the project on time without any labor control actions. In order to investigate the impact of project labor control policies, the base case project was subjected to a temporary increase in the base project rework fraction (from 20% to 40%) that begins at week 20 and ends at week 30. Possible causes of such an increase in rework include the occurrence of unexpected site conditions, utilization of new technology on the project, or a project change order.The ripple effect strength, which describes the interdependency of tasks within the project, was assumed to equal 1, reflection interdependencies that create new work equal to the amount of work discovered to require rework. Figure 4 ("base+rework bump") shows that the project falls behind schedule by 30 weeks after the temporary increase in the rework fraction if no labor controls are used.



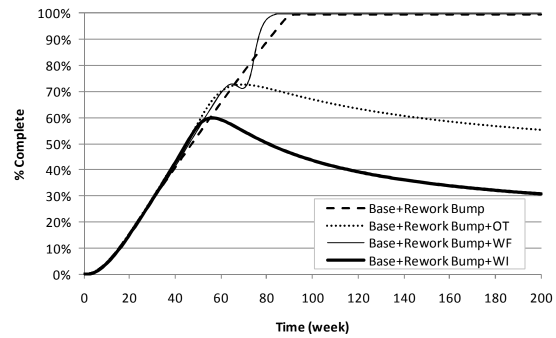


Figure 4: Percent complete of project before after a 20% temporary increase in rework fraction

Figure 5: Percent complete of project utilizing no project labor controls, Overtime (OT), Worforce (WF) or Intensity (WI) policy

In response to the temporary change in the rework fraction, a project manager can decide to employ an overtime, workforce, or intensity policy to correct the poor performance. Initially labor policies that use only one of the three labor tools (i.e. workforce or overtime or work intensity) to address the entire Effective Workforce Deficit were applied (Figure 5). The model displays tipping point behaviors with each labor control policy applied. Figure 5 shows that the use of the work intensity policy results in an initial increase in project performance but eventually the project crosses the tipping point and experiences an indefinate period of decreasing percent complete. This can be explained using the feedback loops identified in Figure 2 and 3. In the beginning (weeks 0-50 in Figure 5), the project improves as the balancing feedback loop B1 (Figure 2) dominates the system. However, increased work intensity causes workers to make more errors instantly, resulting in a continuous increase in rework and project backlog. The shift of dominant feedback loops to R4 (Figure 3) which strenghtnes R1 (Figure 2) then creates tipping point-induced failure (weeks 50-200 in Figure 5).

Figure 5 also shows similar results through the use of the overtime policy. Short periods of overtime use induces an improvement of percent complete performance (weeks 50-63 in Figure 5). However, continuously increasing rework and backlog caused by sustained overtime and fatigue moves the project closer to the tipping point and pushes it past the tipping point to failure (week 65 in Figure 5). During the period of improving project performance (weeks 0-65 in Figure 5) feedback loop B1 (Figure 2) dominates the behavior of the system. When feedback loop R2 (Figure 3) shifts dominance from loop B1 to loop R1 (Figure 2) project performance crosses the tipping point and declines (weeks 65-200 in Figure 5).

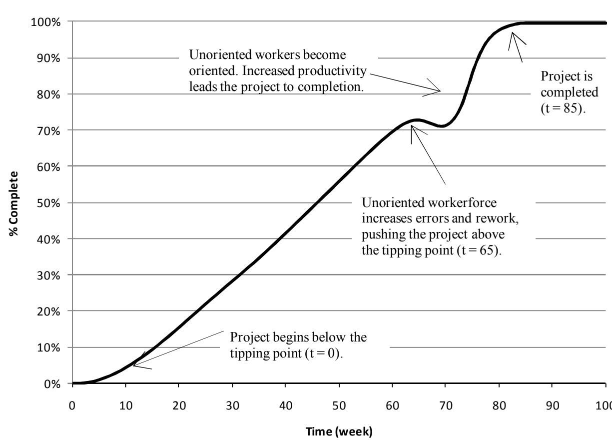


Figure 6: Tipping point behavior of project with workforce policy

Different from the overtime and intensity policies, the utilization of workforce policy results in a project that crosses the tipping point temporarily and subsequently recovers (Figures 5 and 6). As the workforce increases in size from the hiring of new workers, the lack of knowledge and experience causes incremental errors and rework. At week 65 when the rework fraction increases to the maximum, the reinforcing loop R3 (Figure 3) shifts dominance to loop R1 (Figure 2) which pushes the project over the tipping point. After a slight period of degraded performance, the new workforce gains enough experience to complete work faster than they create additional work, Loop B3 (Figure 3) shifts the dominance back to loop B1 (Figure 2), and the project is completed at week 85, eight weeks ahead of the project without control actions (Figure 6).

5. Model Analysis

The model was analyzed using sensitivity testing to identify high leverage parameters that drive project behavior. Sensitivity tests analyze the system's behavior change due to a change of exogenous parameters. In the project control model, parameters that describe overtime, workforce, or intensity policy were analyzed. The range of uncertainty for each parameter was assumed to be (-80%, +100%) from the base case value shown in Table 1.

The concept of project robustness is used to measure the protection that the robustness of a pollicy provides from tipping point failure. Robustness is defined by Taguchi et al. (2000) as "the state where product/process design is minimally sensitive to factors causing variability." The equation that describes project robustness against tipping point-induced failure in the model is as follows (from Taylor and Ford, 2006):

[1] $f_{rw} + (f_{rw} * s_{nt}) + r_{tp} = 1$

where:
f_{mrw} = rework fraction {dimensionless}
s_{nt} = base ripple effect strength {dimensionless}
r_{tp} = robustness to tipping point-induced failure {dimensionless}.

The right side of the equation represents 100% of the project's capacity to tolerate ripple effects without crossing the tipping point (Taylor and Ford, 2006). The value of project robustness (r_{tp}) indicates different system behaviors of the project with a tipping point structure: 1) $r_{tp} > 0$, the project is below (i.e. on the safe side of) tipping point conditions and improving; 2) $r_{tp} < 0$, the project is above tipping point and degrading toward failure; 3) $r_{tp} = 0$, the project is at tipping point conditions and stagnant (no change in percent complete over time).

Figure 7 shows the sensitivity results of the high leverage parameters of the three policies. The horizontal axis represents the percent change of the parameters from base case values (Table 1). The vertical axis represents the project robustness described using Equation 1. For the overtime and intensity policy, the project robustness turns negative when the project crosses tipping point and fails, and vice versa. Thus, the project, under base case conditions of overtime and intensity policy (Table 1), cannot be completed as planned (Figure 5) due to the side effects of the labor control policies. This is shown in the Figure 7 by the negative robustness displayed between 0% and 100% of the percent change in base case value for the parameters "fraction of addition al work dur to WI that requires rework," "fraction of additional work due to OT that requires rework," "average time to overcome WI rework fraction impacts," and the "average time to overcome OT rework fraction impacts." These parameters describe the maginitude of the rework fraction increase per unit use of the OT/WI policy and the time required to recover from the fatigue produced by the use of OT and WI. The negative robustness for these parameters indicate that the project cannot be completed as planned because the project permanetly crosses the tipping point and proceeds to failure as the percent complete decreases over time. For the workforce policy, the negative value of project robustness occurs when project experiences temporary tipping point conditions, since project will be recovered and completed after new workers being oriented. Moreover, a steeper slope indicates the project is more sensitive (less robust) to the changes of model variables. Compared with the other two policies, the intensity policy is more sensitive due to the faster reaction to errors and rework.

The sensitivity results also reveal three important features of the relationship between the high leverage parameters and project robustness. First, the parameters which define how much labor control policies would affect rework fraction ("fraction of additional work due to OT/WI/Unoriented WF that requires rework") and the parameters which describe the recovery from negative impacts of labor control policies ("average time to overcome OT/WI negative impacts", "WF orientation time") are shown to have a large influence over the behavior of the system (Figure 7). Second, the influential parameters of either overtime or intensity policy have idential impacts on project robustness. It is because the parameters of each policy have the same direct relationship with rework induced by project labor controls, and Eq. 1 indicates the changes of rework fraction influences the robustness value directly. Third, each of the high leverage parameters has a threshold value, which determines the polarity of robustness and the tipping point behavior. For example, the threshold value of "fraction of additional work due to OT that requires rework" is approximately -6% of the base case conditions. Any change in this paramter above the threshold value will increase tipping point risks associated with the use of the overtime policy.

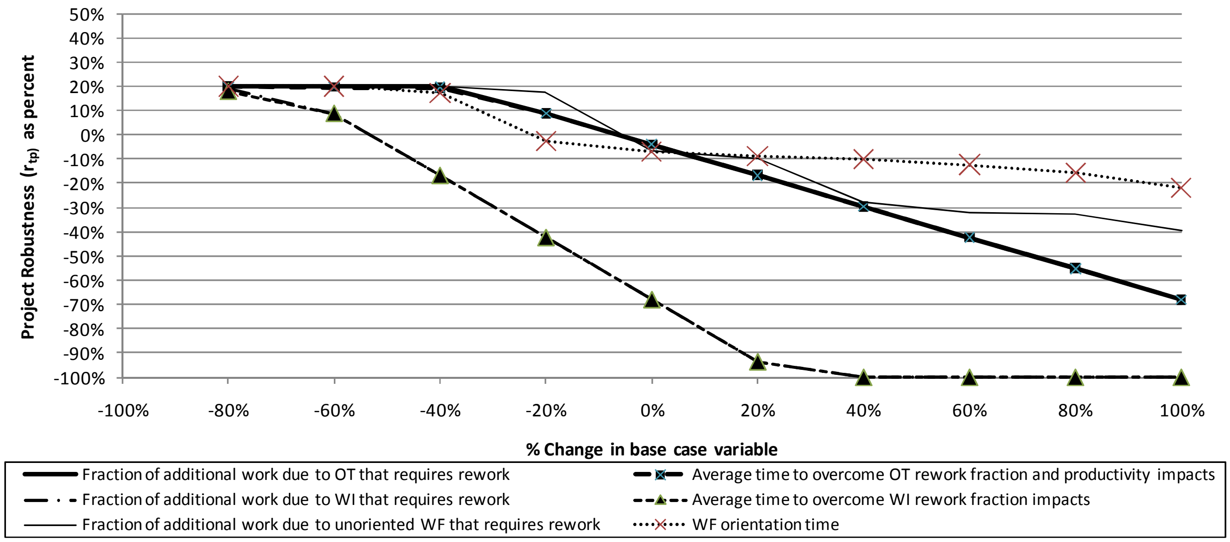


Figure 7: Sensitivity analysis results of Overtime (OT) Policy, Intensity (WI) Policy, and Workforce (WF) Policy

6. Model Use

The analysis of model structures and sensitivity test results offer insights into the use of project labor controls to managing tipping point risks. Due to the feedback structure of the labor control system (Figure 3) the workforce policy is the best solitary policy among the three investigated for correcting poor project performance in project's exposed to tipping point risks. This is because the structure of changing workforce size drives the project to recover from a temporary crossing of the tipping point (for the parameter values used here). After workers becoming oriented, the dominant feedback loops change from R3 (Figure 3) and R1 (Figure 2) to B3 (Figure 3) and B1 (Figure 2), which reduces the rework fraction and project backlogs. However, not all projects are able to increase the size of the workforce due to worker availability, the project budget, and other considerations. Given these common constraints, how can project managers use overtime or work intensity policies to address poor performance on projects and avoid tipping point risks? Based on the sensitivity test results, the threshold values of the high leverage factors provide sufficient evidence for the use of overtime on a project without crossing the tipping point. For example, the manager could target the high leverage parameters "fraction of additional work due to OT that requires rework" and "average time to overcome OT rework fraction and productivity impacts" (Figure 7). On a project these parameters describe how much additional rework is created by fatigue and how fast workers recover from fatigue. Managers could affect these paramters through using occaional overtime instead of prolonged overtime (Hanna, Taylor, and Sullivan 2005), introducing shiftwork (e.g. rotation of workers in high-stress job assisgnments) (CII, 1988), improved training, and innovative work schedule practices (i.e. assigning fresh workers to high rework tasks). Figure 9 displays the schedule performance of the reference project utilizing this improved overtime policy. As expected, the project sucessfully escapes from tipping point conditions and is completed. The more the policy is improved, the sooner the project will be completed. In the case of "OT improved 40%" (i.e. "fraction of additional work due to OT that requires rework" and "average time to overcome OT rework fraction and productivity impacts" are both reduced by 40% from their base values), the project is completed at week 87, six weeks before the project without any control policies applied.

Project managers who only have the work intensity policy available to address poor project performance can also reduce tipping point risks by using strategies that target high leverage parameters. Figure 7 shows that the parameters "fraction of additional work due to WI that requires rework" and "average time to overcome WI rework fraction impacts" have a significant impact on the performance of the work intensity policy in avoiding tippoing point dynamics. As with the overtime policy a number of strategies are available to target these parameters for improvement: capacity adjustment (i.e. allocating more of the project workforce to high-intensity work) and creating quality pressure (Oliva and Sterman 2001). The instant feedback structure of work intensity also suggests that the effectiveness of this policy is improved if used over a short period of time. Instead of employing throughout project execution, a 5-week application since the temporary increase in rework fraction helps to complete the project at week 92 ("WI improved 40% (Week 20-25)", Figure 10). However, with improved either overtime policy or intensity policy, the project is still behind schedule ("initial input deadline" = 65 weeks, Table 1).

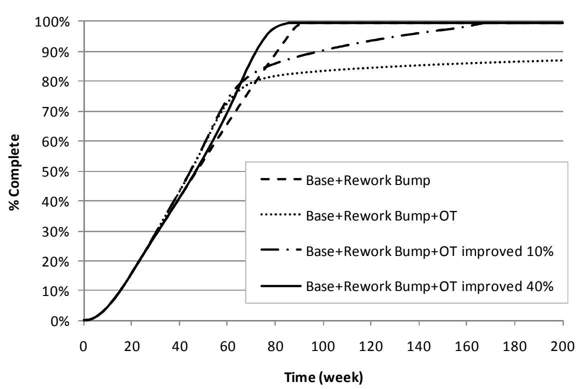


Figure 9: Percent complete of project with rework bump before and after Overtime (OT) Policy being improved

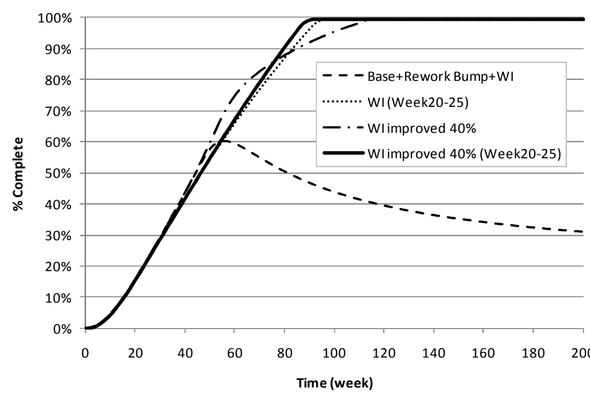


Figure 10: Percent complete of project with rework bump before and after Intensity (WI) Policy being improved

7. Conclusions

This paper examines the tipping point behavior of a system dynamics model which simulates a construction project with three traditional project labor control policies (workforce, overtime, and intensity policy). A project labor control model describes the application process of project control policies and the rework induced process by the side effects of project controls. The dominance shift of balancing or reinforcing feedback loops is used to explain the tipping point dynamics. The work demonstrates that the labor control policies can push a project that otherwise would recover past the tipping point and into a period of declining project progress. The increased workforce labor control policy provides the most robustness to tipping point dynamics due to the temporary nature of side effects from this policy. The use of overtime and work intensity can push a project past the tipping point if used for long periods of time. But these policies can be used, provided the project manager is able to adequately influence the ability of the workers to avoid creating additional mistakes and overcome the effects of worker fatigue.

This work contributes to the application of tipping point dynamics in the design of effective project labor controls by modeling anddemonstrating the impacts of a new, management-induced mechanism of tipping point dynamics in the form of the increased rework associated with the use of commonly applied project labor controls. This expands the description of potential causes of tipping point project failures beyond changes from outside the project (e.g. change orders that increase rework) to include manager-created tipping point dynamics. This improved understanding of project tipping point dynamics can be used in future work to address the use of multiple labor controls(e.g. temporary use of overtime followed by a more permanent increase in the workforce) to correct poor project perfomrance.

For managers of project's susceptible to tipping point dynamics, the current work offers a number of insights. First, increasing the size of workforce is the most robust labor control policy due to the feedback structure interaction. Overtime and work intensity can be used to correct poor project performance but they require additional management action to prevent these policies from pushing the project past the tipping point. However, the use of overtime and work intensity results in significantly poorer schedule performance when compared with the workforce policy.

The model used in this work can be improved in several ways. The current work provides adequate support to help projects avoid tipping point-induced failures by using project control policies seperately. However, the improvement is not enough to complete the project on schedule. Future research can focus on project control design to improve eventual schedule performance by combining different policies.

8. References

Abdel-Hamid, T. K. 1984. *The Dynamics of Software Development Project Management: An Integrative Systems Dynamics Perspective*. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, USA.

Black, L. and Repenning, N. 2001. Why firefighting is never enough: preserving high-quality product development. *System Dynamics Review.* 17(1): 33-62.

Construction Industry Institute (CII). 1988. *The Effects of Scheduled Overtime and Shift Schedule on Construction Craft Productivity*. Austin, TX.

Friedrich, D. R., Daly, J. P., and Dick, W. G. 1987. Revisions, Repairs, and Rework on Large Projects. *ASCE Journal of Construction Engineering and Management*. 113(3): 488-500.

Eden, C., Williams, T., and Howick S. 2000. The Role of Feedback Dynamics in Disruption and Delay on the Nature of Disruption and Delay in Major Projects. *Journal of the Operational Research Society*, 51 (3): 291-300.

Ford, D. N., Lyneis, J. M., and Taylor, T. 2007. Project Controls to Minimize Cost and Schedule Overruns: A Model, Research Agenda, and Initial Results. *Proceedings of the 2007 International System Dynamics Conference*, Boston, MA, USA, 2007.

Hanna, Award S., Taylor, Craig S., and Sullivan, Kenneth T. 2005. Impact of Extended Overtime on Construction Labor Productivity. *ASCE Journal of Construction Engineering and Management*. 131(6) pp.734-739

Lyneis, J., Ford, D. 2007. System Dynamics Applied to Project Management: A Survey, Assessment, and Directions for Future Research. *System Dynamics Review*, 23(2/3): 157-189.

Lundgren, E. F. and Schneider, J. V. 1971. A Marginal Cost Model for the Hiring-Overtime Decision. *Management Science*. 17(6): 399-405.

Oliva, R. and Sterman, J.D. 2001. Cutting Corners and Working Overtime: Quality Erosion in the Service Industry. *Management Science*. 47(7): 894-914.

Repenning, N. 2001. Understanding fire fighting in new product development. *Journal of Product Innovation Management*. 18(2001): 265-300.

Sterman, J. D. 2000. *Business Dynamics: Systems Thinking and Modeling for A Complex World*. Irwin McGraw-Hill, Boston, MA, USA.

Taylor, T. and Ford, D. 2006. Tipping Point Failure and Robustness in Single Development Projects. *System Dynamics Review*. 22 (1): 51-71.

Taylor, T. and Ford, D. 2008. Managing Tipping Point Dynamics in Complex Construction Projects. *ASCE Journal of Construction Engineering and Management*. 134(6): 421-431.

Taguchi. G., Chowdhury. S., and Taguchi. S. 2000. *Robust Engineering*. McGraw-Hill: New York.

Thomas, R. and Raynar, K. A. 1997. Schedule Overtime and Labor Productivity: Quantitative Analysis. *Journal of Construction Engineering and Management*. ASCE, 123(2): 181-188.

Wang, Y., Goodrum, P. M., Haas, C. T., and Glover, R. W. 2008. Craft Training Issues in American Industrial and Commercial Construction. *Journal of Construction Engineering and Management*, 134(10), 795-803.

[i] In this model, resource costs are assumed to include all other project costs. Costs in the design phase of construction projects are commonly measured this way.