System Dynamics Applied to Outsourcing Engineering Services in Design Build-Projects

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ABSTRACT

This study developed a system dynamics model for determining the outcome for outsourcing engineering services in the large and complex project organizational structure that is typically associated with design-build project delivery. A literature review was performed on the application of system dynamics for outsourcing of engineering services in design-build projects. For the most part, the reviewed papers indicate the additional engineering resources provided were totally insourced or the authors were silent regarding any resources that were outsourced. A system dynamics model to account for the impacts of outsourcing various percentages of the engineering services to sustain a design-build project over a specified time horizon was developed using Vensim software. The results of running this model indicate that the amount and timing of engineering task work completed depends upon both the productivity and quality of the outsourced engineering services as well as the initial number of experienced engineers. The system dynamics model was validated, and compared well with actual data from a $3 billion design-build transit project.

KEY WORDS

Design-Build, System Dynamics, Professional Engineering, Outsourcing, Project Management, Quality, Productivity, Staffing, Tasks, Rework, Learning Curve, Modeling.

INTRODUCTION

System dynamics (SD) is founded in the work of J. W. Forrester (1961) and is a methodology to model, understand, and predict the real world behaviors of large and complex systems.

The cause and effect relationships of variables within subsystems can be depicted by creating causal loop diagrams. The causal loop linkages are either positive (reinforcing) or negative (balancing) and are represented in Figure 1. These also assist in understanding the feedback mechanisms with the SD model, and lead to the development of stock and flow diagrams.

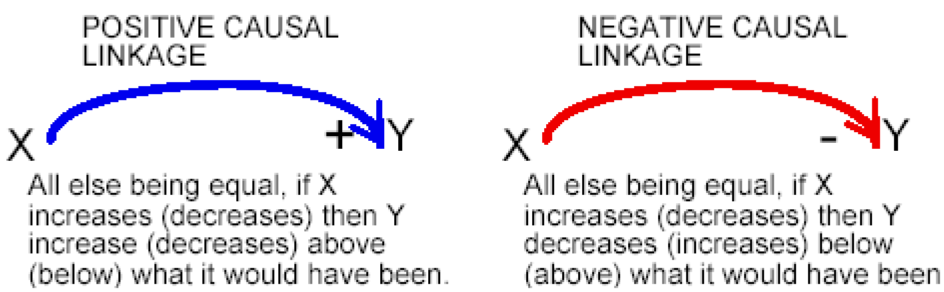

Figure 1: Causal Loop Linkages from Scott (2002)

The underlying structure of the system is represented by the mathematical equations between the variables in the stock and flow diagram. Stocks are the representations of levels variables, such as products, and flows are rates, such as products produced per day. So the stocks allow decisions to be made and flows are changed in the system under study. Figure 2 shows a depiction of a stock and flow diagram.

Figure 2: General Stock and Flow from Scott (2002)

The ability of owners and managers to execute large and complex infrastructure projects is dependent upon implementing best engineering practices that realize affordability and cost management. It is becoming increasingly imperative to provide quality engineering services within existing and projected budgetary and time constraints.

Outsourcing services on large, complex, long-term projects may only produce short-term profitability, and may negatively impact project and organizational sustainability. By insourcing engineering services, the project organizational core competencies are increased, leading to both long-term financial and operational sustainability.

By using system dynamics (SD), the performance of engineering services can be expressed as a feedback model that can enable project managers to understand how an engineering problem developed over time, and assist in finding a lasting solution to the problem. The system dynamic approach incorporates subjective factors that have important influences on the whole design-build project.

Accordingly, the SD model will enable managers to prudently decide what, if any, project engineering services to outsource in lieu of in-house accomplishment in order to satisfy the design-build project financial and time requirements.

LITERATURE REVIEW

Huot and Cooper (1982) discussed using system dynamics to model large projects strategy management by three primary components. Those components are: the state of the system, the rates of change, and the information networks. In a series of causal loops, the impacts of engineering productivity to engineering productivity were linked to give project management decision makers a dynamic tool to access project schedule outcomes. Construction problems can form reinforcing loops and become larger project problems as shown in Figure 3.

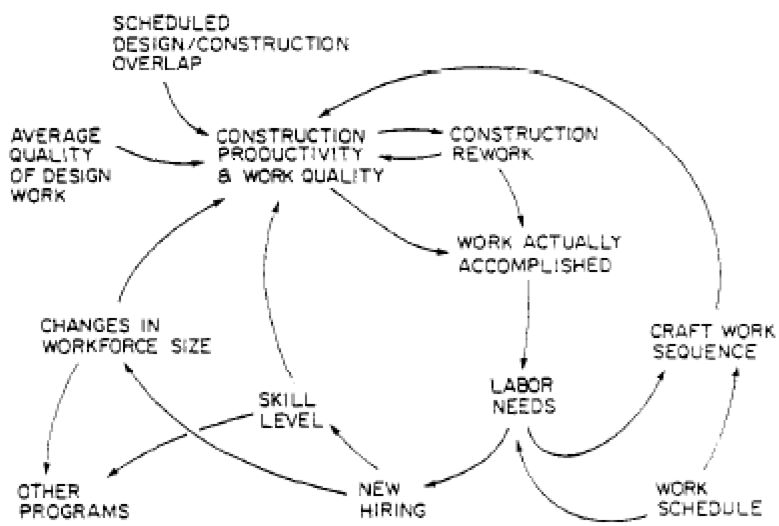

Figure 3: Reinforcement of construction problems from Huot and Cooper (1982)

Braunschweig and Huot (1984) used the MINISAMI micro-version of Program Management Modeling System (PMMS) to model design accomplishment with the number of drawings achieved. The two concepts in this model were the productivity (the rate at which drawings are produced) and the quality (the percentage of drawings that will not require rework). A resultant causal loop model for Manpower Assignment and

Performance Indicators was developed, and showed schedule slippage for added design work after the initial design had been completed. This model is shown below in Figure 4.

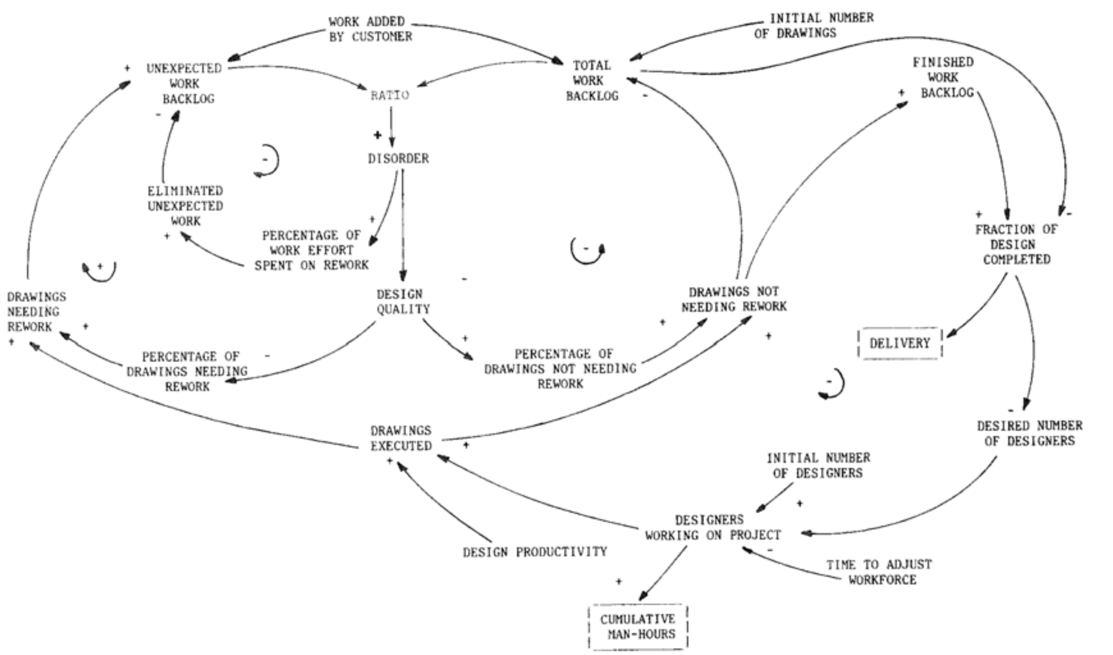

Figure 4: Manpower assignment and performance indicators from Braunschweig and Huot (1984)

Rodrigues and Bowers (1996) developed a system dynamics model of the human resource management cycle to analyze the project control cycle. This study analyzed the impact of the following three parameters on project duration: the productivity, the number of staff working, and the work rate. However, a detailed schedule and traditional network analysis was also needed for project control. The human resource management cycle studied is shown in Figure 5.

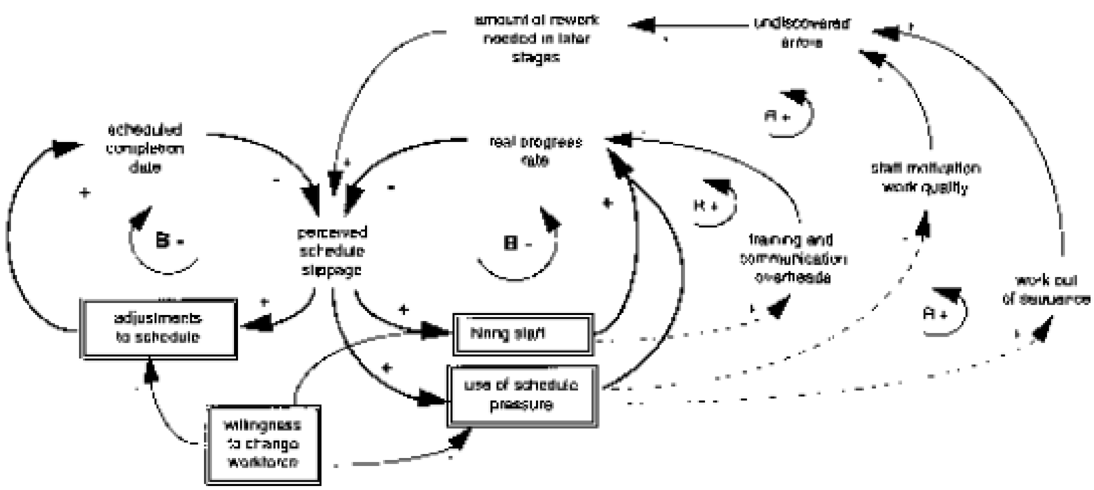

Figure 5: Human resource management cycle from Rodrigues and Bowers (1996)

In 1998, Chapman studied how system dynamics could assist in understanding the impact a change of key project personnel had on design production and design duration. It was found that design development was dependent upon the quality and extent of integration of differentiated engineering skills. The resulting model of the design process showed staff change had a negative impact on: the orientation phase, the training overhead, the communication overhead, hiring delays, and the leaving rate. The model is shown in Figure 6.

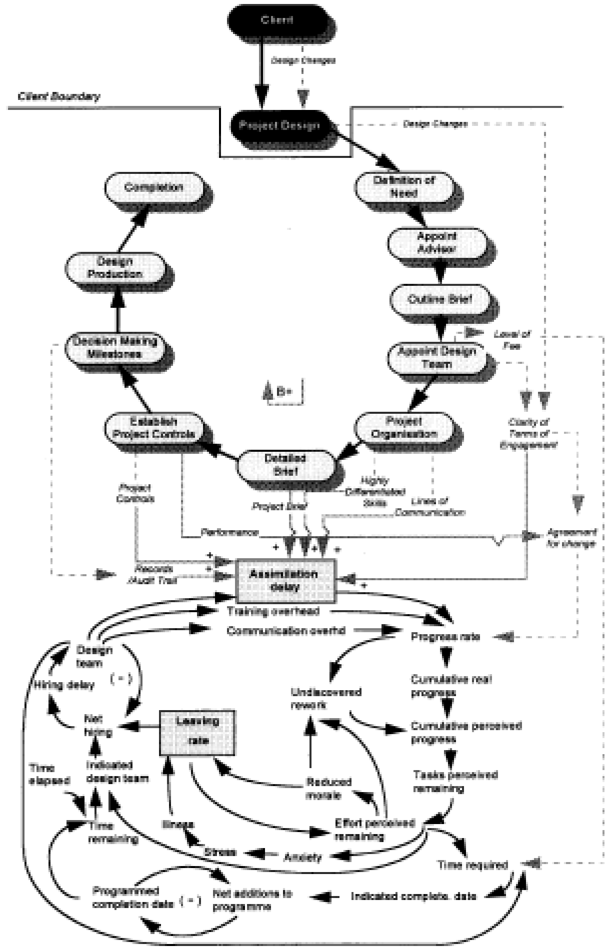

Figure 6: Model of the design process illustrating the negative impact of a change of staff from Chapman (1998)

Ogulana et al. (1998) developed a model for the detailed design process of a civil engineering project. That model mainly consisted of three casual loops: a goal seeking or negative feedback loop with two stocks which determines the work force level available, a negative feedback loop with three stocks that determines productivity and adjusts the workload, and a positive feedback loop with three stocks that controls how schedule date is maintained. However, this model, as shown in Figure 7, was valid only for a design staff of 10 or more personnel, so was unable to be applied to other projects.

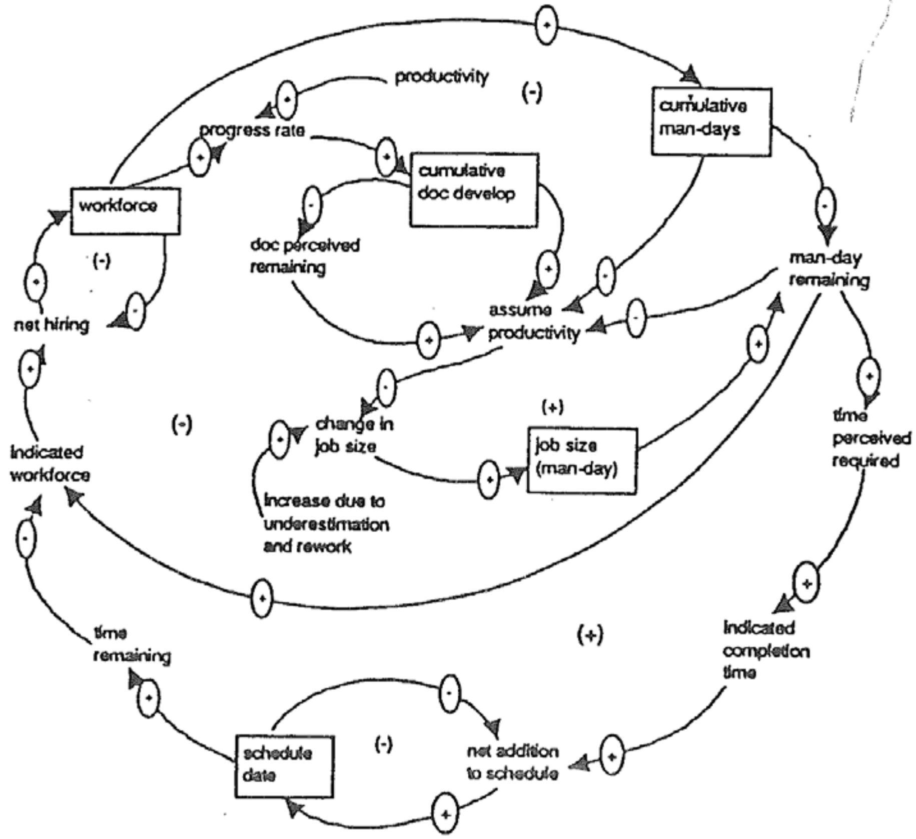

Figure 7: Major feedback loops for design project model from Ogulana et al. (1998)

Love et al. (2002) described how changes impact project performance using system dynamic methodology. The two basic sources of dynamics that infringe upon a project system include: 1) planned activities with attended dynamics-factors resulting from active interventions, and 2) uncertainties with unattended dynamics-factors beyond the control of project management. Findings from this case study indicated that 50 percent of rework costs resulted from the poor motivation levels of the architects and engineers. The causal loop diagram of the system dynamics project management model is presented below in Figure 8.

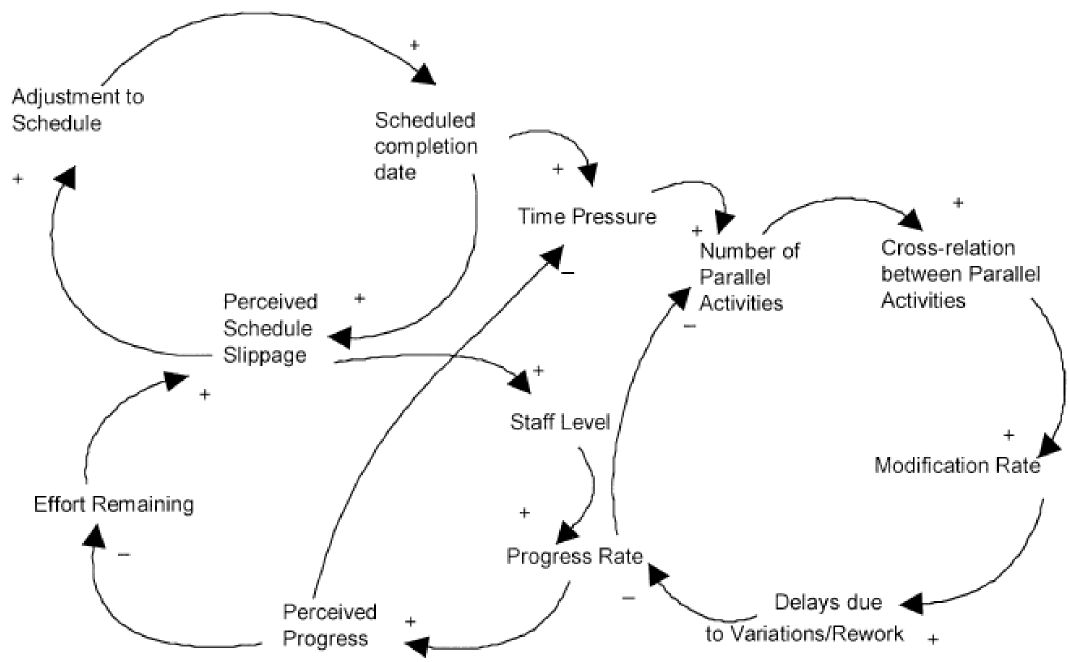

Figure 8: Causal loop diagram of the project management model from Love et al. (2002)

Park (2005) proposed a model-based dynamic approach for engineering resource (labor and material) management. The model simulation of the resource level targeting process indicated that there is a time-cost tradeoff of resource coverage and project performance. Also, policy implications were discussed for the key variables listed as target material level, target workforce level, material acquisition rate, and workforce based engineering rate. These models are presented below in Figure 9.

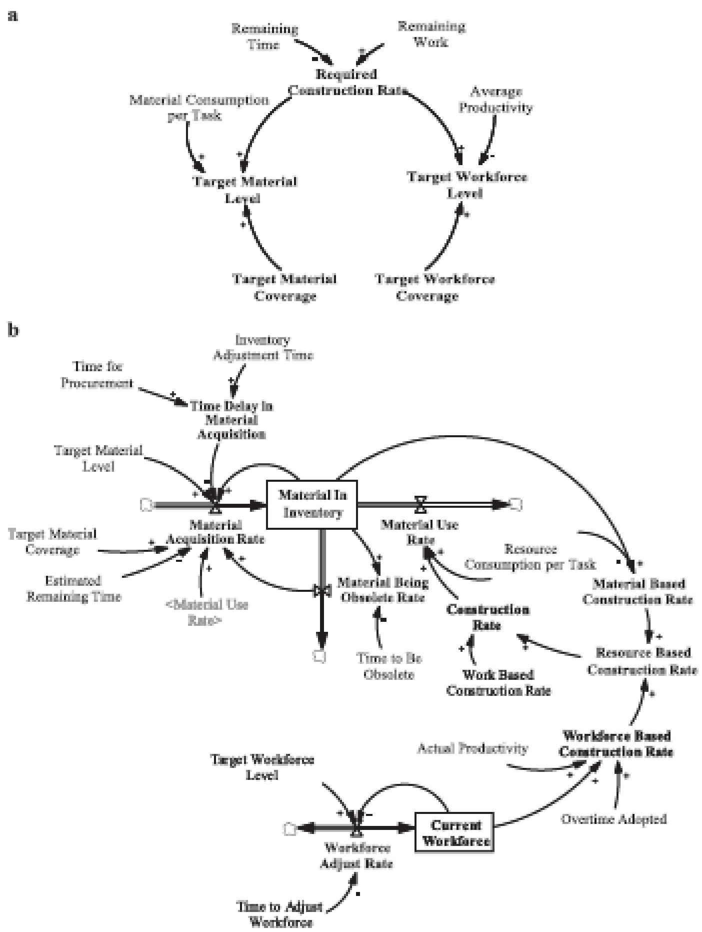

Figure 9: (a) Resource level targeting process. (b) Resource based construction rate from Park (2005)

Closely following the above, Lee, Pena-Mora and Park (2006) introduced the system's perspective of dynamic planning and control methodology to support the strategic and operational aspects of project management. The integration of traditional CPM approach and system dynamics modeling by Vensim was developed into a project management tool with characteristics that included a strategic core of system dynamics, a tactical layer of agent-based modeling, an operational layer of network-based tools, optimization techniques, discrete-event simulation and statistics, and an interface layer with Gantt chart, dependency structure matrix, smart cell, behavioral graph and 4D visualization. This methodology of modeling change management with system dynamics is shown in the below Figure 10.

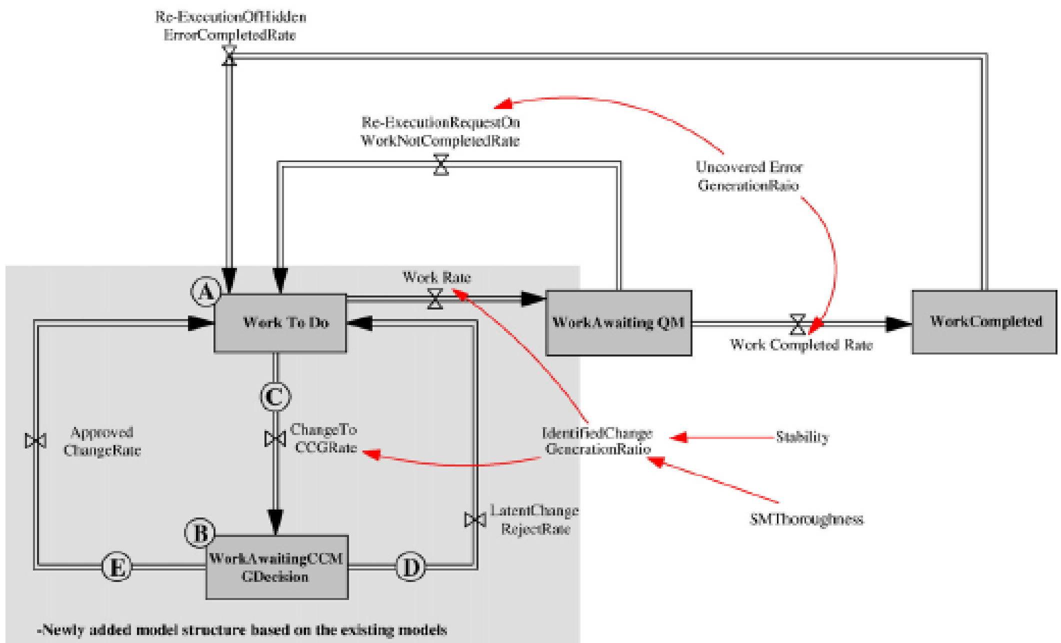

Figure 10: Modeling change management with system dynamics from Lee et al. (2006)

In 2010, Minami et al. used system dynamics methodology to model the engineering process, and conducted simulations to examine the impact of project management decisions. They concluded that increased constructability efforts and design sharing mitigated the impact of cost overruns and project completion delays. Also, the study concluded that it is best to focus improvement efforts early in the project when limited resources exist. Figure 11 shows the SD model used for task flow in construction design.

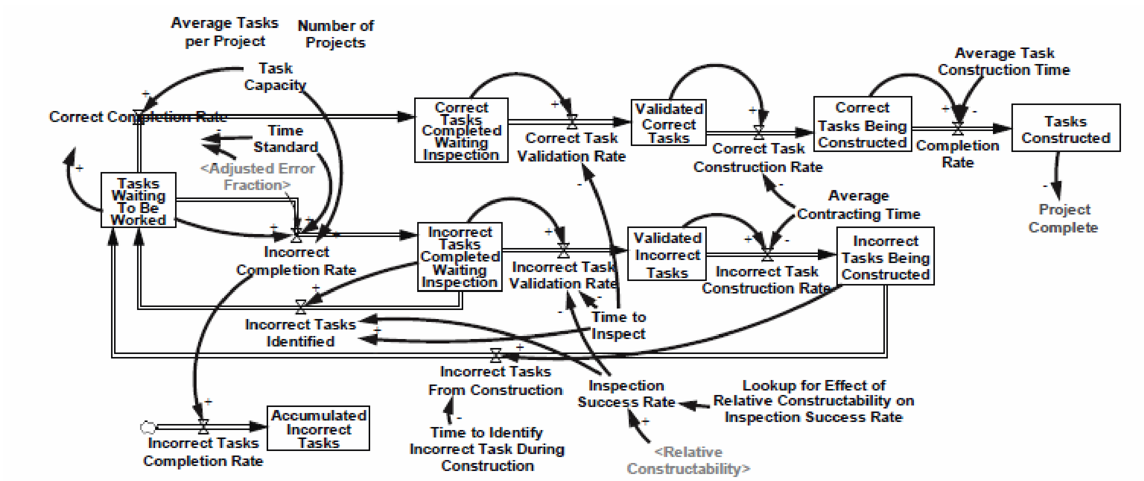

Figure 11: Task flow in construction design from Minami et al. (2010)

Han et al. (2012) have recently developed a system dynamics model to capture the dynamics of design errors, and systematically assess their negative impacts. Rework due to design errors and changes are considered to be the primary contributor to schedule delay and cost overruns in design-build projects. The research indicated that, despite the continuous schedule recovery efforts by project managers, design errors can significantly delay the project schedule. Furthermore, it is shown that schedule pressure can propagate negative impacts to various construction activities not associated with the design errors. The generic work execution module is shown in Figure 12.

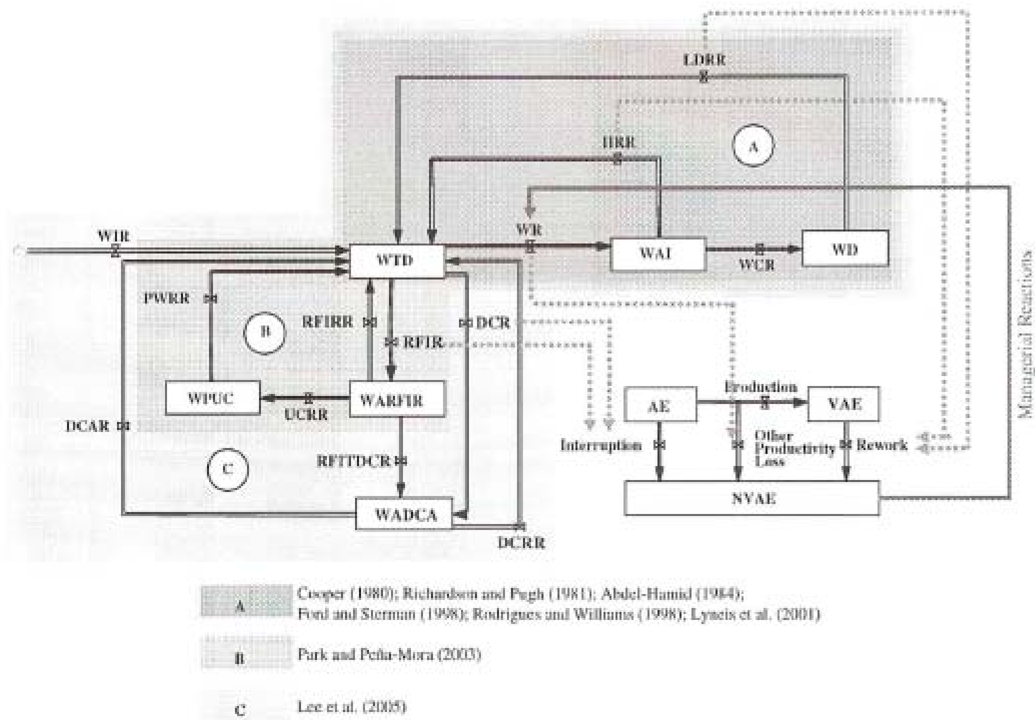

Figure 12: Generic work execution module from Han et al. (2012)

In 2012, Lisse developed a preliminary system dynamics model of outsourced construction services in large shipbuilding projects, which are comparable to design-build projects. Vensim software was utilized, and the most productive use of total construction effort was shown to be 20%-90% outsourced for the project parameters used. However, this SD model did not account for changed construction work, nor changed scheduled project completion date, and was subsequently modified as indicated within this study.

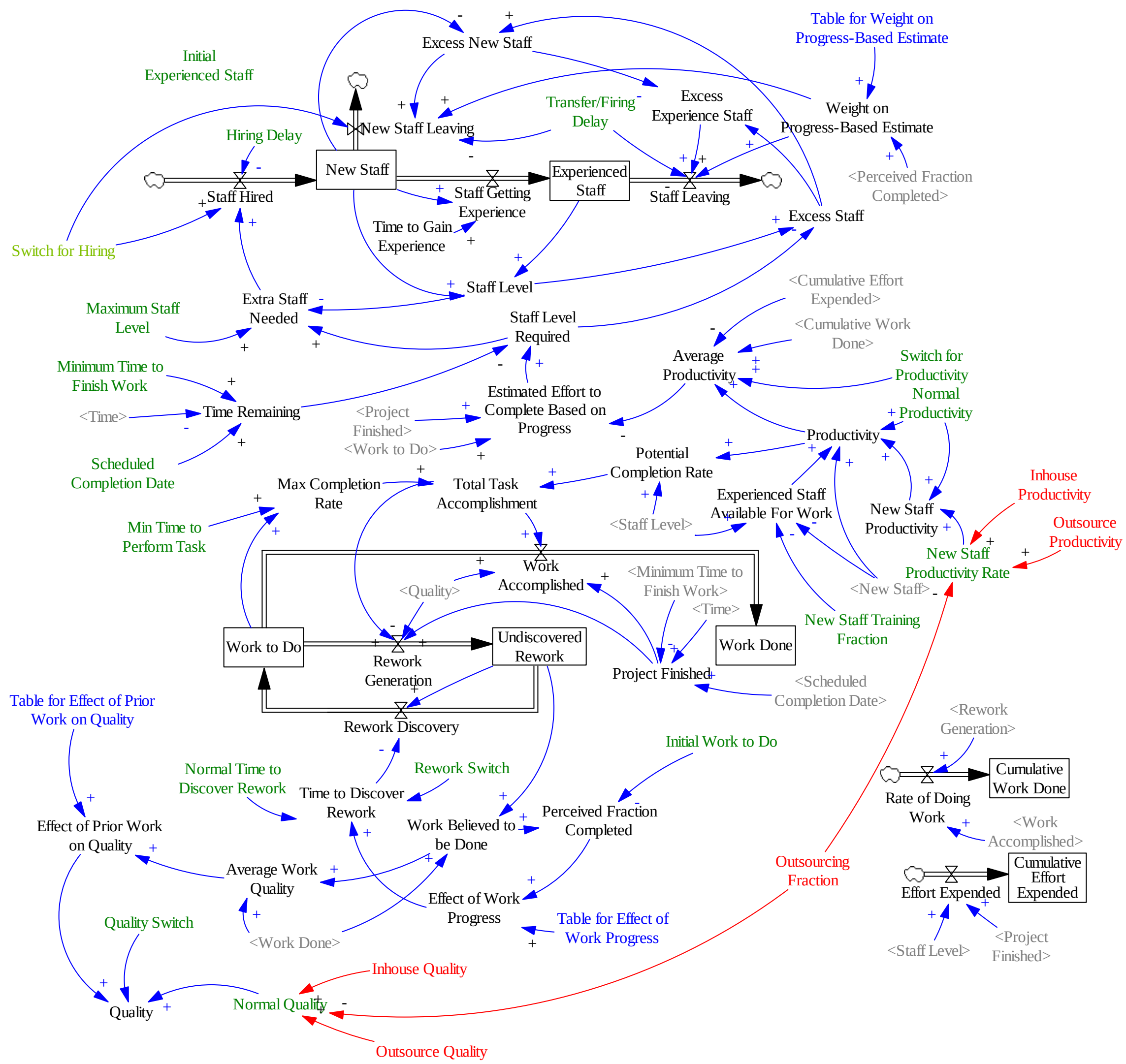

Figure 13: SD model with outsourcing construction resources from Lisse (2012)

SD MODEL

This literature review indicates that a successfully engineered design-build project depends upon the quantity, productivity, and quality of the professional engineering services. However, almost all of the reviewed papers indicated the additional engineering resources provided were totally insourced or the authors were silent regarding any resources that were outsourced. Thus, one would have to assume that these reviewed studies involved insourced professional engineering resources unless otherwise indicated.

A system dynamics model was developed using Vensim software to account for the impacts of outsourcing a percentage of the required professional engineering services to sustain a design-build project over a specified time horizon. This SD model is a refinement of the previous model, as it includes the impacts from changed work and associated changed project scheduled completion date. It is shown in Figure 14, and the model variables are listed in the following section.

In this study, the required project engineering expertise was not an available core competency of the in-house design-build project engineering staff, so that service required outsourcing. Therefore, the outsourced engineering resources had higher productivity and quality factors than the in-house resources. Also, there were initially ten experienced engineers available for the initial engineering workload of 60 tasks over 60 days. As the project progressed, the work scope increased by 10 tasks at Day 50 and the associated scheduled completion date was extended by 10 days.

The design-build model parameters used for this study include the following variables:

1. Initial scheduled completion date: 60 days
2. Revised scheduled completion date: 70 days
3. Changed work scope at: Day 50
4. Initial experienced staff: 3 people
5. Maximum staffing: 10 people
6. Initial engineering work: 60 tasks
7. Added engineering work: 10 tasks

8. In-house quality factor: 0.9
9. Outsourced quality factor: 1
10. In-house productivity factor: 0.06 task/(day*people)
11. Outsourced productivity factor: 0.1 task/(day*people)

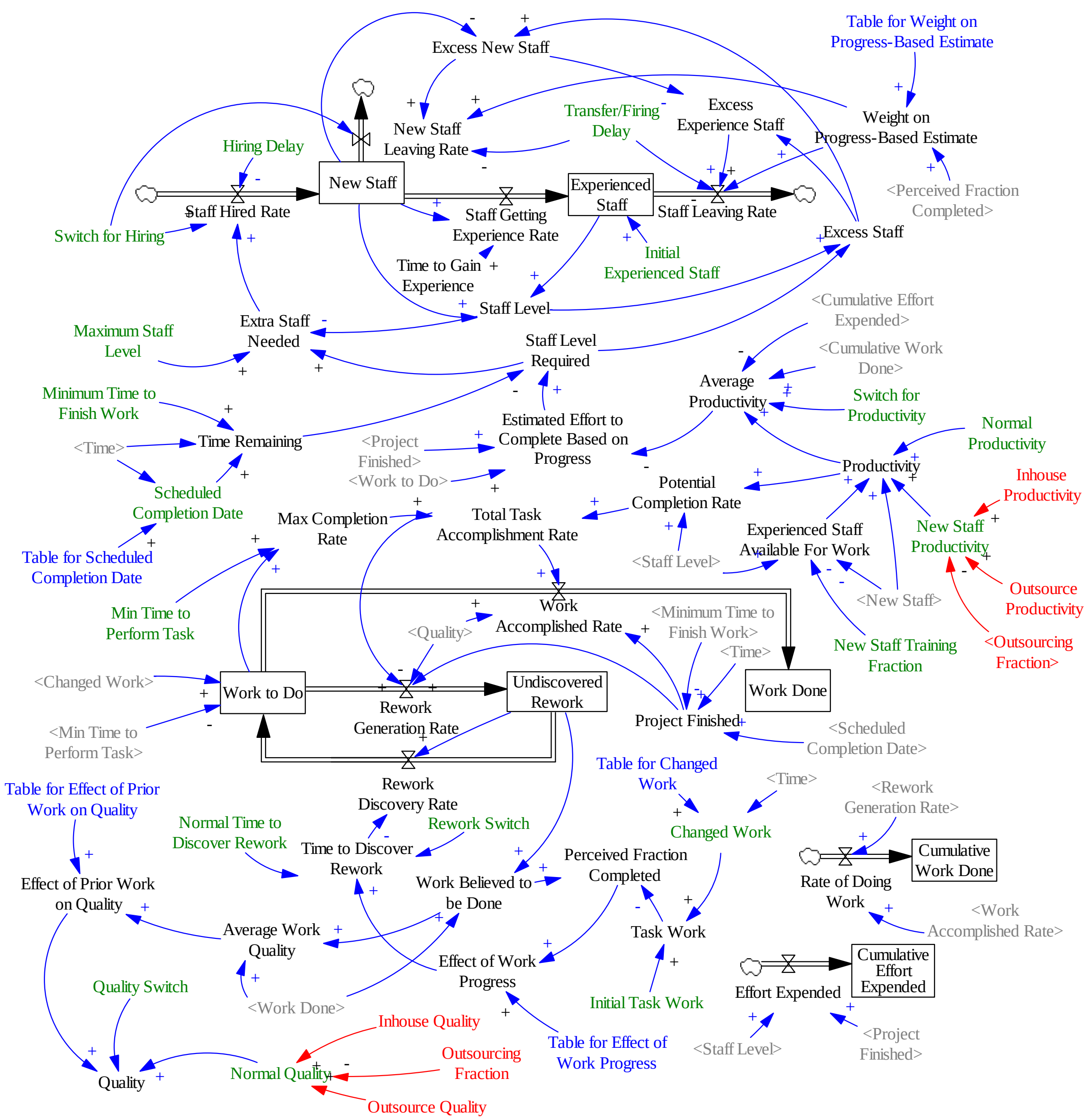

Figure 14: SD model for outsourcing engineering services in a design-build project

RESULTS

The average work quality of the engineering services on the design-build project by the percentage of outsourcing is shown in Figure 15. As indicated, all cases progress through the project to the normal quality value of 1. As anticipated, the 100% outsourcing case achieves the normal quality value earlier than the others, and it maintains that quality factor even after the engineering work scope increases by 10 tasks at Day 50.

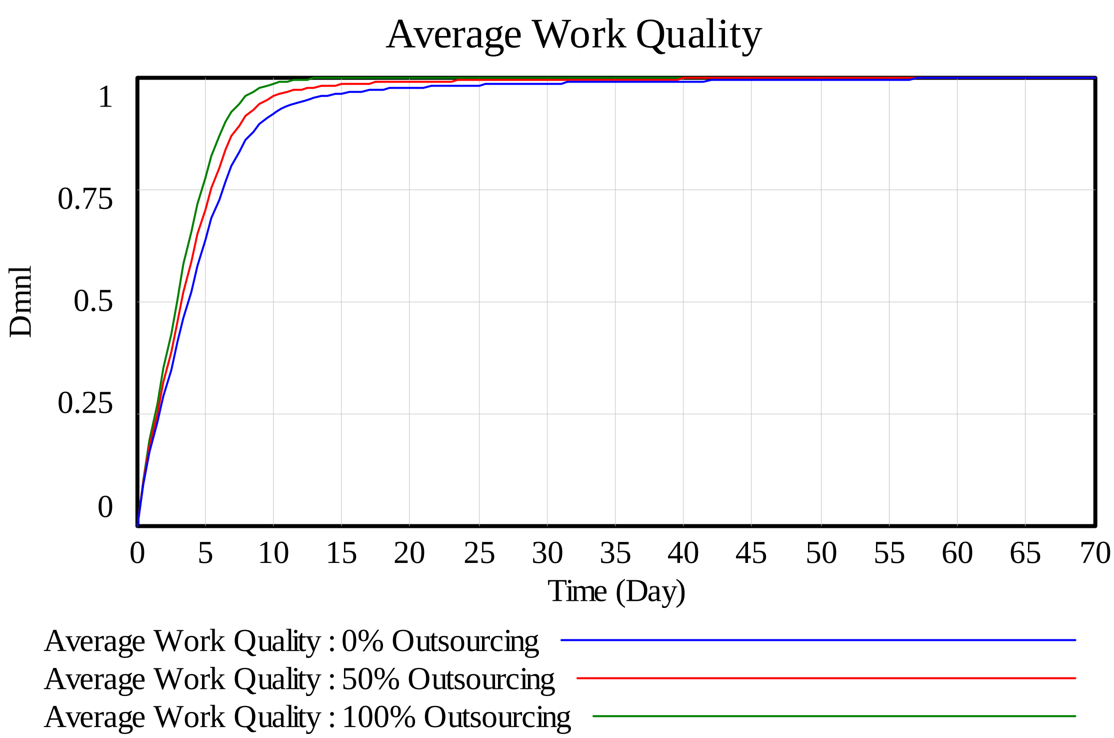

Figure 15: Average work quality for engineering services on the design-build project

The average engineering productivity for the studied engineering services is shown in Figure 16, and Table 1 provides a summary of average productivity values. For this study, the normal productivity factor used was 0.1 task/(people*day). All cases commenced engineering work by early building up to the normal value and decreased productivity as new engineers were assigned to the design-build project. As expected, the 100% outsourced case had the least overall productivity impacts during the project duration, in part because fewer new engineers were needed to complete the increased workload of 70 tasks.

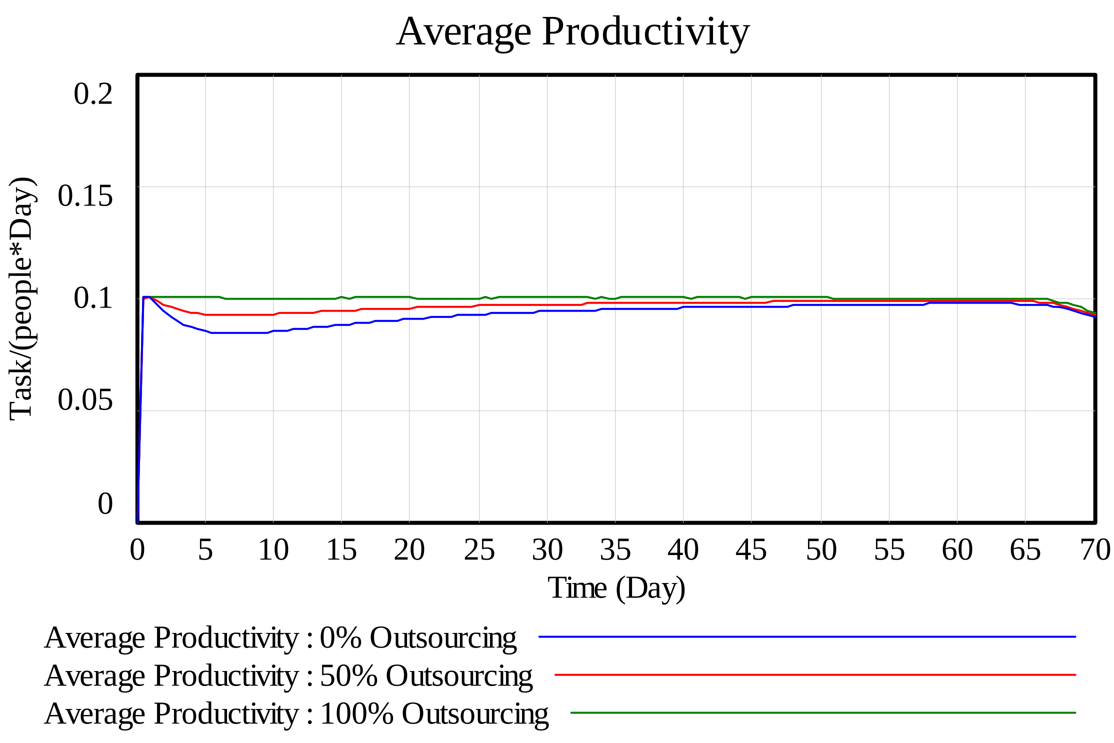

Figure 15: Average productivity for engineering services on the design-build project

AVERAGE PRODUCTIVITY (Task/(people*Day))			
	Outsourcing Percentage		
Time (Day)	0%	50%	100%
0	0	0	0
5	0.085	0.093	0.100
10	0.085	0.093	0.100
15	0.088	0.094	0.100
20	0.091	0.096	0.100
25	0.093	0.096	0.100
30	0.094	0.097	0.100
35	0.095	0.098	0.100
40	0.096	0.098	0.100
45	0.096	0.098	0.100
50	0.097	0.098	0.100
55	0.097	0.099	0.100
60	0.097	0.099	0.100
65	0.097	0.098	0.099
70	0.092	0.092	0.093

Table 1: Summary of average engineering productivity for the design-build project

The engineering tasks completed as the percentage of outsourcing in the design-build project is shown in Figure 16, and Table 2 provides a summary of the work done. It is shown that as the outsourcing percentage increases, the amount of engineering tasks completed over the project duration increases. As shown in Table 2, the 100% outsourcing case achieved the required 70 tasks completion at the revised scheduled project completion date, whereas the other cases fell short of completing the assigned tasks.

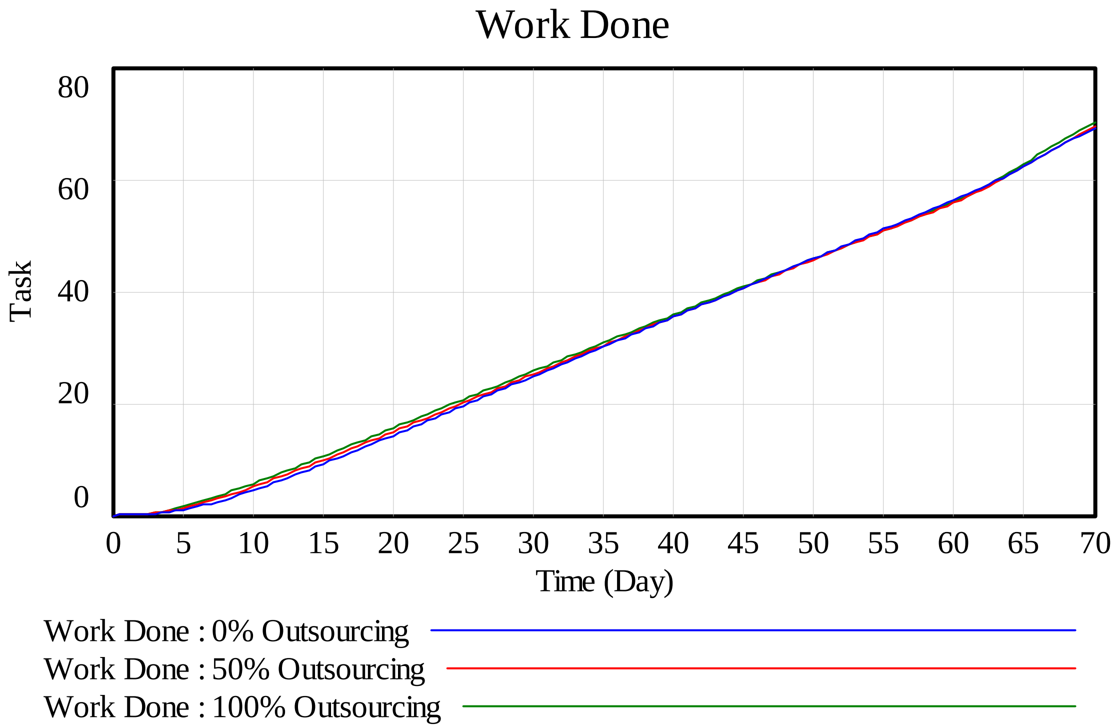

Figure 16: Engineering tasks completed in the design-build project

WORK DONE (Tasks)			
	Outsourcing Percentage		
Time (Day)	0%	50%	100%
0	0	0	0
5	1	1	2
10	4	5	6
15	9	10	11
20	14	15	16
25	20	20	21
30	25	25	26
35	30	30	31
40	35	35	36
45	41	41	41
50	46	46	46
55	51	51	51
60	56	56	56
65	62	62	63
70	69	69	70

Table 2: Summary of engineering tasks completed in the design-build project

The engineering staff level for the studied engineering work is shown in Figure 17. The 100% outsourcing case exhibits the least manning level over the duration of the design-build project. From project commencement, the initial experienced staff required augmentation by additional assigned engineers to the project in all cases. If the initial experienced staff could be increased, then the staffing level required at project completion would have decreased. The other cases always required higher staffing levels due to lower overall quality and productivity factors which necessitated assignment of additional engineers beyond the maximum project level.

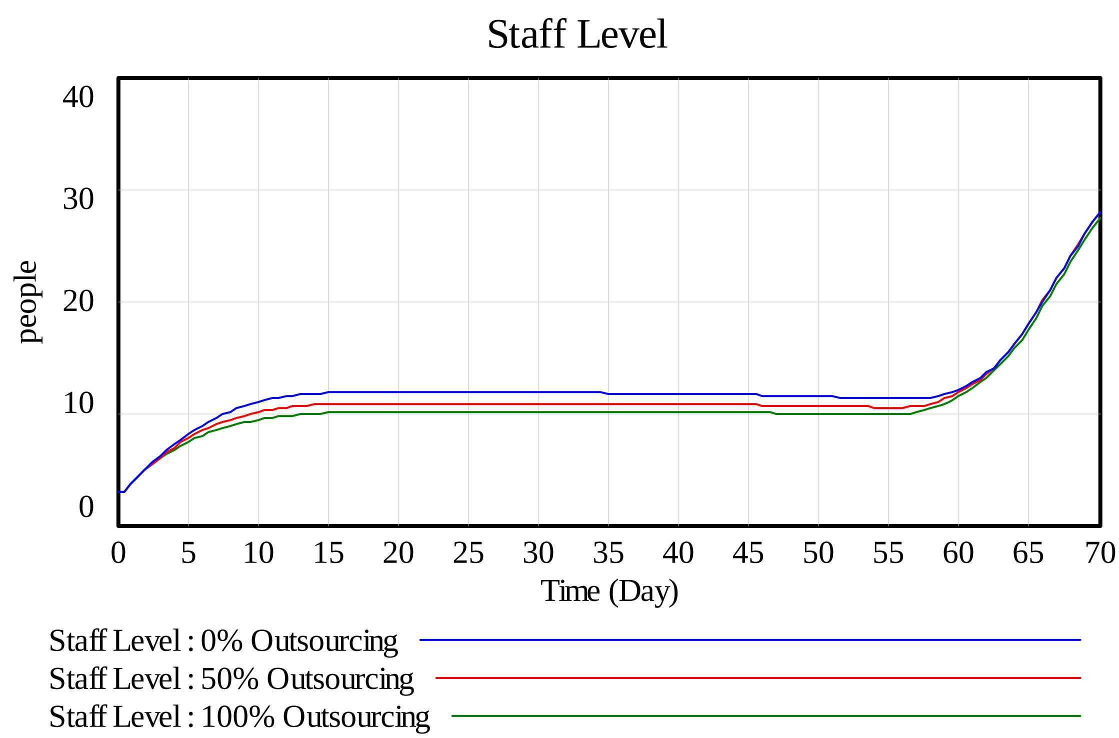

Figure 17: Engineering staff level in the design-build project

SD MODEL VALIDATION

Sterman (2000) on Page 846 indicates that "…validation and verification of models is impossible." However, the developed system dynamics model as shown in Figure 13 and listed in the Attachment must be tested to understand its limitations and to improve it. Some model tests suggested by Sterman that were performed are summarized below.

Face Validity

Face validity is usually an iterative process that compares the causal loop, and stock and flow diagrams with the real world system that is modeled. A qualitative decision was made as to the accuracy with which the system dynamics model portrays the actual system under study. The SD model accurately describes the cost estimating services in a design-build project, including instances of changed/additional work and changed scheduled completion dates.

Structure Assessment Tests

Partial model tests were conducted of the decision rules and strategy rationale. Policy structure diagrams, causal loop, and stock and flow diagrams were inspected, as well as model equations to verify relevant descriptive knowledge of the system.

Dimensional Consistency Tests

Each equation was inspected for dimensional consistency and suspect parameters were modified. Use of parameters with no real world meaning was avoided.

Integration Error Tests

The SD model was not sensitive to the choice of time step or integration method in the Vensim software expected to be used for the modeling.

Extreme Conditions Tests

The model made sense even when its inputs took on extreme values, including policies, shocks, and parameters. The model results were inspected when responding to extreme values of each input, by itself or in combination. These tests verified model conformance to basic physical laws.

Behavior Reproduction Tests

The SD model reproduced both the quantitative and qualitative behavior of interest in the system. Statistical measures of correspondence between the model and data were computed by running the model and comparing results for a sample of 8 design-build cost estimates as shown in Table 3. The standard deviation was 0.707 days with duration variances ranging from 2.564% to -7.692% with a mean of -1.407%, which is adequate.

Model output and data was also compared qualitatively for modes of behavior, shape of variables, asymmetries, relative amplitudes and phasing, and unusual events.

Design-Build Project Estimating Effort Comparison with SD Model									
Estimate No.	Estimators (People)	Initial Tasks	Outsourced %	Added Tasks	Actual Duration (Days)	SD Duration (Days)	Actual-SD (Days)	Variance %	Standard Deviation
1	4	4	25	0	25	25	0	0.000	0.000
2	6	6	50	0	39	38	1	2.564	0.707
3	12	12	75	0	26	26	0	0.000	0.000
4	4	4	100	2	47	48	-1	-2.128	0.707
5	2	2	0	0	14	14	0	0.000	0.000
6	2	2	0	2	25	26	-1	-4.000	0.707
7	2	2	0	0	25	25	0	0.000	0.000
8	4	4	100	0	13	14	-1	-7.692	0.707
Totals					214	216	-2	-0.935	

Table 3: Design-build project cost estimating effort comparison with SD model

Sensitivity Analysis

The robustness of the model to the uncertainty in the research assumptions was analyzed, including numerical, behavioral, and policy sensitivity. Analytic methods were used to determine the best parameters and policies. Optimization methods were not necessary due to satisfactory estimated results. Parameter combinations that generated implausible results or reverse policy outcomes were eliminated.

System Improvement Tests

The impact of the modeling process on the mental models, behavior, and outcomes for the enterprise was assessed. Modifications to the preliminary model were made to make the system perform better under changed/added work and changed scheduled completion dates, which reflected the project's operations.

CONCLUSIONS

There is a paucity of available literature on insourcing versus outsourcing engineering services on major design-build (combination of design/engineering) projects. From the results of this literature review and system dynamics modeling, the decision to insource/outsource engineering services on design-build projects may have significant cost (and time) impacts which should be considered by decision makers.

The developed SD model incorporated design scope changes and associated project completion date changes, producing related impacts to the design-build project. The model was validated and modeled outcomes for 8 different cost estimating work tasks, which compared well to actual data from a $3 billion transit project. Additional analysis of various initial numbers of experienced engineers assigned, the changed tasks, and changed timing of engineering tasks will be performed in a future study.

REFERENCES

Braunschweig, B. and Huot, J.C., A System Dynamic Project Management Model, *1984 AACE Transactions*, D.2, AACE International, Morgantown, WV, 1984.

Chapman, R.J., The Role of System Dynamics in Understanding the Impact of Changes to Key Project Personnel on Design Production Within Engineering Projects, *International Journal of Project Management*, Vol. 16, No. 4, pp. 235-247, 1998.

Forrester, F.W., Industrial Dynamics, Cambridge, MA, MIT Press, 1961.

Han, S., Love, P. and Pena-Mora, F., A System Dynamics Model for Assessing the Impacts of Design Errors in Construction Projects, *Mathematical and Computer Modelling*, In Press, DOI:10.1016/j.mcm.2011.06.039, 2012.

Huot, J.C, and Cooper, K.G., Large Project Dynamics, *1982 AACE Transactions*, T-1, AACE International, Morgantown, WV, 1982.

Lee, S.H., Pena-Mora, F. and Park, M., Dynamic Planning and Control Methodology for Strategic and Operational Engineering Project Management, *Automation in Engineering*, Vol. 15, pp. 84-97, 2006.

Lisse, S.D., System Dynamics of Outsourcing Construction in Shipbuilding Projects, *Proceedings of American Society of Naval Engineers Day 2012 Symposium*, Arlington, Virginia, February 2012.

Love, P., Holt, G., Shen, L., Li, H. and Irani, Z., Using Systems Dynamics to Better Understand Change and Rework in Engineering Project Management Systems, *International Journal of Project Management*, Vol. 20, No. 6, pp. 425-436, 2002.

Minami, N.A, Soto, L.L. and Rhodes, D.H., Dynamic Lean Management of the Naval Engineering Process, *Engineering Management Journal*, Vol. 22, No. 2, pp. 36-43, 2010.

Ogunlana, S., Lim, J. and Saeed, K., Desman: A Dynamic Model for Managing Civil Engineering Design Projects, *Computers and Structures*, Vol. 67, No. 5, pp. 401-419, 1998.

Park, M., Model-based Dynamic Resource Management for Engineering Projects, *Automation in Engineering*, Vol. 14, pp. 585-598, 2005.

Rodrigues, A. and Bowers, J., The Role of System Dynamics in Project Management, *International Journal of Project Management*, Vol. 14, No. 4, pp. 213-220, 1996.

Scott, J.M., A System Dynamics Model of the Operations, Maintenance and Disposal Costs of New Technologies for Ship Systems, *MS Thesis, Systems Engineering*, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2002.

Sterman, J.D., Business Dynamics: systems thinking and modeling for a complex world, Boston, McGraw-Hill, 2000.

ATTACHMENT

SD Model Variables

(01) Average Productivity=Switch for Productivity * ZIDZ(Cumulative Work Done, Cumulative Effort Expended) + (1-Switch for Productivity) * Productivity
Units: Task/(people*Day)
(02) Average Work Quality=MIN(1,ZIDZ(Work Done , Work Believed to be Done))
Units: Dmnl
(03) Changed Work=Table for Changed Work(Time)
Units: Task
(04) Cumulative Effort Expended= INTEG (Effort Expended,0)
Units: people*Day
(05) Cumulative Work Done= INTEG (Rate of Doing Work,0)
Units: Task
(06) Effect of Prior Work on Quality=Table for Effect of Prior Work on Quality(Average Work Quality)
Units: Dmnl
(07) Effect of Work Progress=Table for Effect of Work Progress(Perceived Fraction Completed)
Units: Dmnl
(08) Effort Expended=IF THEN ELSE(Project Finished, 0, Staff Level)
Units: people
(09) Estimated Effort to Complete Based on Progress=IF THEN ELSE(Project Finished, 0, ZIDZ(Work to Do, Average Productivity))
Units: people*Day
(10) Excess Experience Staff=MAX(0, Excess Staff-Excess New Staff)
Units: people
(11) Excess New Staff=MAX(0, Excess Staff-New Staff)
Units: people
(12) Excess Staff= MAX(0, Staff Level-Staff Level Required)
Units: people
(13) Experienced Staff= INTEG (Staff Getting Experience Rate-Staff Leaving Rate, Initial Experienced Staff)
Units: people
(14) Experienced Staff Available For Work=Staff Level-New Staff-New Staff Training Fraction*New Staff
Units: people
(15) Extra Staff Needed=MIN(Maximum Staff Level, MAX(0, Staff Level Required-Staff Level))
Units: people
(16) FINAL TIME = 70
Units: Day
The final time for the simulation.
(17) Hiring Delay= 5
Units: Day
(18) Inhouse Productivity= 0.06
Units: Dmnl
(19) Inhouse Quality=0.9
Units: Dmnl
(20) Initial Experienced Staff=3

Units: people
(21) Initial Task Work=60
Units: Task
(22) INITIAL TIME = 0
Units: Day
The initial time for the simulation.
(23) Max Completion Rate=Work to Do/Min Time to Perform Task
Units: Task/Day
(24) Maximum Staff Level=10
Units: people
(25) Min Time to Perform Task=10
Units: Day
(26) Minimum Time to Finish Work=5
Units: Day
(27) New Staff= INTEG (Staff Hired Rate-New Staff Leaving Rate-Staff Getting Experience Rate,0)
Units: people
(28) New Staff Leaving Rate="Weight on Progress-Based Estimate"*Excess New Staff*"Transfer/Firing Delay"*Switch for Hiring
Units: people/Day
(29) New Staff Productivity=Inhouse Productivity*(1-Outsourcing Fraction)+ Outsource Productivity*Outsourcing Fraction
Units: Dmnl
(30) New Staff Training Fraction= 0.25
Units: Dmnl
(31) Normal Productivity=0.1
Units: Task/(Day*people)
(32) Normal Quality=Inhouse Quality*(1-Outsourcing Fraction)+Outsource Quality*Outsourcing Fraction
Units: Dmnl
(33) Normal Time to Discover Rework=3
Units: Day
(34) Outsource Productivity=0.1
Units: Dmnl
(35) Outsource Quality=1
Units: Dmnl
(36) Outsourcing Fraction=1
Units: Dmnl
(37) Perceived Fraction Completed=MIN(1,ZIDZ(Work Believed to be Done, Task Work))
Units: Dmnl
(38) Potential Completion Rate=Staff Level*Productivity
Units: Task/Day
(39) Productivity=(New Staff*New Staff Productivity+Experienced Staff Available For Work*Normal Productivity)/(New Staff+Experienced Staff Available For Work)
Units: Task/people/Day
(40) Project Finished=IF THEN ELSE(Scheduled Completion Date+Minimum Time to Finish Work-Time<=0, 1, 0)
Units: Dmnl
(41) Quality=Quality Switch * Normal Quality * Effect of Prior Work on Quality + (1 - Quality Switch) * Normal Quality

Units: Dmnl
(42) Quality Switch=1
Units: Dmnl [0,1]
(43) Rate of Doing Work=Rework Generation Rate+Work Accomplished Rate
Units: Task/Day
(44) Rework Discovery Rate=Undiscovered Rework/Time to Discover Rework
Units: Task/Day
(45) Rework Generation Rate=IF THEN ELSE(Project Finished, 0 , Total Task Accomplishment Rate*(1-Quality))
Units: Task/Day
(46) Rework Switch=1
Units: Dmnl [0,1]
(47) SAVEPER = TIME STEP
Units: Day [0,?]
The frequency with which output is stored.
(48) Scheduled Completion Date=Table for Scheduled Completion Date(Time)
Units: Day
(49) Staff Getting Experience Rate=MAX(0, New Staff/Time to Gain Experience)
Units: people/Day
(50) Staff Hired Rate=MAX(0, (Extra Staff Needed/Hiring Delay)*Switch for Hiring)
Units: people/Day
(51) Staff Leaving Rate=Excess Experience Staff*"Weight on Progress-Based Estimate"*"Transfer/Firing Delay"
Units: people/Day
(52) Staff Level=MAX(0, Experienced Staff+New Staff)
Units: people
(53) Staff Level Required= Estimated Effort to Complete Based on Progress/Time Remaining
Units: people
(54) Switch for Hiring=1
Units: Dmnl [0,1]
(55) Switch for Productivity=1
Units: Dmnl [0,1]
(56) Table for Changed Work((0,0)-(70,10)],(0,0),(49.999,0),(50,10),(70,10))
Units: Task
(57) Table for Effect of Prior Work on Quality([(0,0.1)-(1,1)],(0,0.1),(0.1,0.25),(0.2,0.35),(0.3,0.45),(0.4,0.55),(0.5,0.675),(0.6,0.775),(0.7,0.85),(0.8,0.95),(0.9,0.99),(1,1))
Units: Dmnl
(58) Table for Effect of Work Progress([(0,1)-(1,0.05)],(0,1),(0.1,1),(0.2,1),(0.3,1),(0.4,1),(0.5,1),(0.6,0.95),(0.7,0.8),(0.8,0.45),(0.9,0.2),(1,0.05))
Units: Dmnl
(59) Table for Scheduled Completion Date([(0,60)-(70,70)],(0,60),(49.999,60),(50,70),(70,70))
Units: Day
(60) "Table for Weight on Progress-Based Estimate"([(0,0)-(1,1)],(0,0),(0.1,0),(0.2,0),(0.3,0.1),(0.4,0.25),(0.5,0.5),(0.6,0.75),(0.7,0.9),(0.8,1),(0.9,1),(1,1))
Units: Dmnl
(61) Task Work=Initial Task Work+Changed Work
Units: Task

(62) Time Remaining=MAX(Minimum Time to Finish Work, Scheduled Completion Date-Time)
Units: Day

(63) TIME STEP = 0.5
Units: Day [0,?]
The time step for the simulation.

(64) Time to Discover Rework=Rework Switch * Normal Time to Discover Rework*Effect of Work Progress + (1 - Rework Switch) * Normal Time to Discover Rework
Units: Day

(65) Time to Gain Experience=5
Units: Day

(66) Total Task Accomplishment Rate=MIN(Max Completion Rate, Potential Completion Rate)
Units: Task/Day

(67) "Transfer/Firing Delay"=0.0083
Units: 1/Day

(68) Undiscovered Rework= INTEG (Rework Generation Rate-Rework Discovery Rate,0)
Units: Task

(69) "Weight on Progress-Based Estimate"="Table for Weight on Progress-Based Estimate"(Perceived Fraction Completed)
Units: Dmnl

(70) Work Accomplished Rate=IF THEN ELSE(Project Finished, 0, Total Task Accomplishment Rate*Quality)
Units: Task/Day

(71) Work Believed to be Done=Undiscovered Rework+Work Done
Units: Task

(72) Work Done= INTEG (Work Accomplished Rate,0)
Units: Task

(73) Work to Do= INTEG (Rework Discovery Rate-Rework Generation Rate-Work Accomplished Rate+Changed Work /Min Time to Perform Task,Task Work)
Units: Task

AUTHOR

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