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Research article

Applying System Dynamics for Outsourcing Naval Engineering Services

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Abstract

This study developed a system dynamics model for determining the outcome for outsourcing design work in a naval engineering project. A literature review was performed on the application of system dynamics for outsourcing of resources in engineering 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 naval engineering project over a specified time horizon was developed using Vensim software. Results of running this model indicate that the amount of effort of the studied engineering work depends upon both the productivity and quality of the outsourced services as well as project manning constraints. The percent of outsourcing engineering work may also produce schedule overrun in the overall time to complete those required work tasks in the shipbuilding project.

Keywords: System dynamics, outsourcing, project management, quality, naval engineering, productivity, shipbuilding

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Introduction

System dynamics (SD) is founded in the work of J. W. Forrester and is a methodology to model, understand, and predict real world behaviors of large and complex systems [1].

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 [2]. These also assist with understanding the feedback mechanisms with the SD model and lead to the development of stock and flow diagrams.

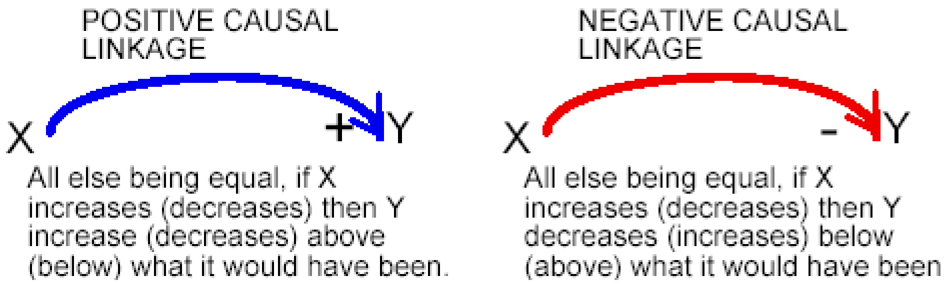

Figure 1: Causal Loop Linkages

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 [2].

Figure 2: General Stock and Flow

Additionally, in system dynamics modeling, table functions (also called lookup tables) are used to represent nonlinear relationships between two variables and are easier to interpret and to visualize than complex algebraic functions.

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

Outsourcing services on naval engineering projects may produce short-term profitability and may also have negative impacts upon the 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 management 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 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 project financial and time requirements. Additionally, if outsourcing of services is required due to the unavailability of specific design resources, the SD model will forecast the outcomes associated with that decision.

This study describes a SD model for performing engineering work tasks in a project organization typical of shipbuilding. In the following sections, a literature review is discussed, the SD model and results are described, the SD model is validated, and conclusions are presented.

Literature Review

In 1982, Huot and Cooper discussed system dynamics to model large projects strategy management by three primary components [3]. 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 construction productivity to engineering productivity were linked to give project management decision makers a dynamic tool to access project schedule outcomes. Accordingly, engineering problems can form reinforcing loops and become larger project problems.

Later, Rodrigues and Bowers developed a system dynamics model of the human resource management cycle to analyze the project control cycle [4]. This study analyzed the impact upon project duration of the following three parameters: 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.

Also, Laverghetta and Brown used the Naval Design Process (NDP) system dynamics model to demonstrate the sensitivity of policy options regarding the trade of cost, schedule and performance on a naval shipbuilding program [5]. It was concluded that system dynamics modeling is not intended for daily operational management of a project which should rely on computerized project management. Also, the NDP model did not explicitly address the issues of ship manufacturing or competing design efforts.

In 2002, Love et al. described how changes impact project performance using system dynamic methodology [6]. The two basic sources of dynamics that infringe upon a project system include planned activities with attended dynamics-factors resulting from active interventions, and uncertainties with unattended dynamics-factors beyond the control of project management. Findings from this case study indicated that 50 percent of the rework costs resulted from poor motivation levels of the architects and engineers.

Next, Park proposed a model-based dynamic approach for construction resource (labor and material) management [7]. The model simulation of the resource level targeting process indicated there is a time-cost tradeoff of resource coverage and project performance. Also, policy implications were discussed for the key variables listed as the target material level, the target workforce level, the material acquisition rate, and the workforce based engineering rate.

Closely following the above, Lee, Pena-Mora and Park introduced the system's perspective of dynamic planning and control methodology to support the strategic and operational aspects of project management [8]. The integration of traditional CPM approach and system dynamics modeling by Vensim was developed into a project management tool whose characteristics 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, 4D visualization. Thereby, the SD model was feed updated data as the project progressed.

Minami et al. used system dynamics methodology to model the naval engineering process and conducted simulations to examine the impact of project management decisions [9]. 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.

In 2012, Han et al. developed a system dynamics model to capture the dynamics of design errors and systematically assess their negative impacts [10]. Rework due to design errors and design 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, the design errors can significantly delay the project schedule. Further, it is shown that schedule pressure can propagate negative impacts to various construction activities not associated with the design errors.

Then, Lisse developed a system dynamics model of the outsourcing of construction services in large shipbuilding projects [11]. 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 in this study.

More recently, Lisse developed a system dynamics model for outsourcing construction services which also accounted for impacts of changed work [12]. Results indicated that the amount of effort of construction work depends upon both the productivity and quality of the outsourced construction services as well as project manning constraints. The percent of outsourcing construction work may also produce schedule overrun in the overall time to complete the required work tasks in the construction project.

Results

This literature review indicates that the success of engineering in a shipbuilding project depends upon both the productivity and quality of the engineering services. Additionally, all workers new to the naval engineering project exhibit a learning curve while accommodating to the project organization and culture. However, the vast majority of 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 engineering resources.

A system dynamics model to account for the impacts of outsourcing a percentage of the required engineering design services to sustain a shipbuilding project over a time horizon of 2 months was developed using Vensim software. This SD model is a variance of the model previously presented for outsourcing construction services [12], and contains 297 feedback loops. It is shown in Figure 3, and the model variables are listed in the Appendix.

In this study, the required project engineering expertise was an available core competency of the in-house project staff, so that service did not required full outsourcing. Also, the outsourced engineering resources had lower productivity and quality factors than the in-house resources. Additionally, there were initially six experienced engineers available for the initial engineering workload of 8 tasks over 2 months.

The construction model parameters used for this study include the following variables:

- Initial scheduled completion date: 2 months
- Initial experienced staff: 6 people
- Maximum staffing: 10 people
- Initial construction work: 8 tasks
- In-house quality factor: 1

- Outsourced quality factor: 0.8
- In-house productivity factor: 1 task/(month*people)
- Outsourced productivity factor: 0.85 task/(month*people)

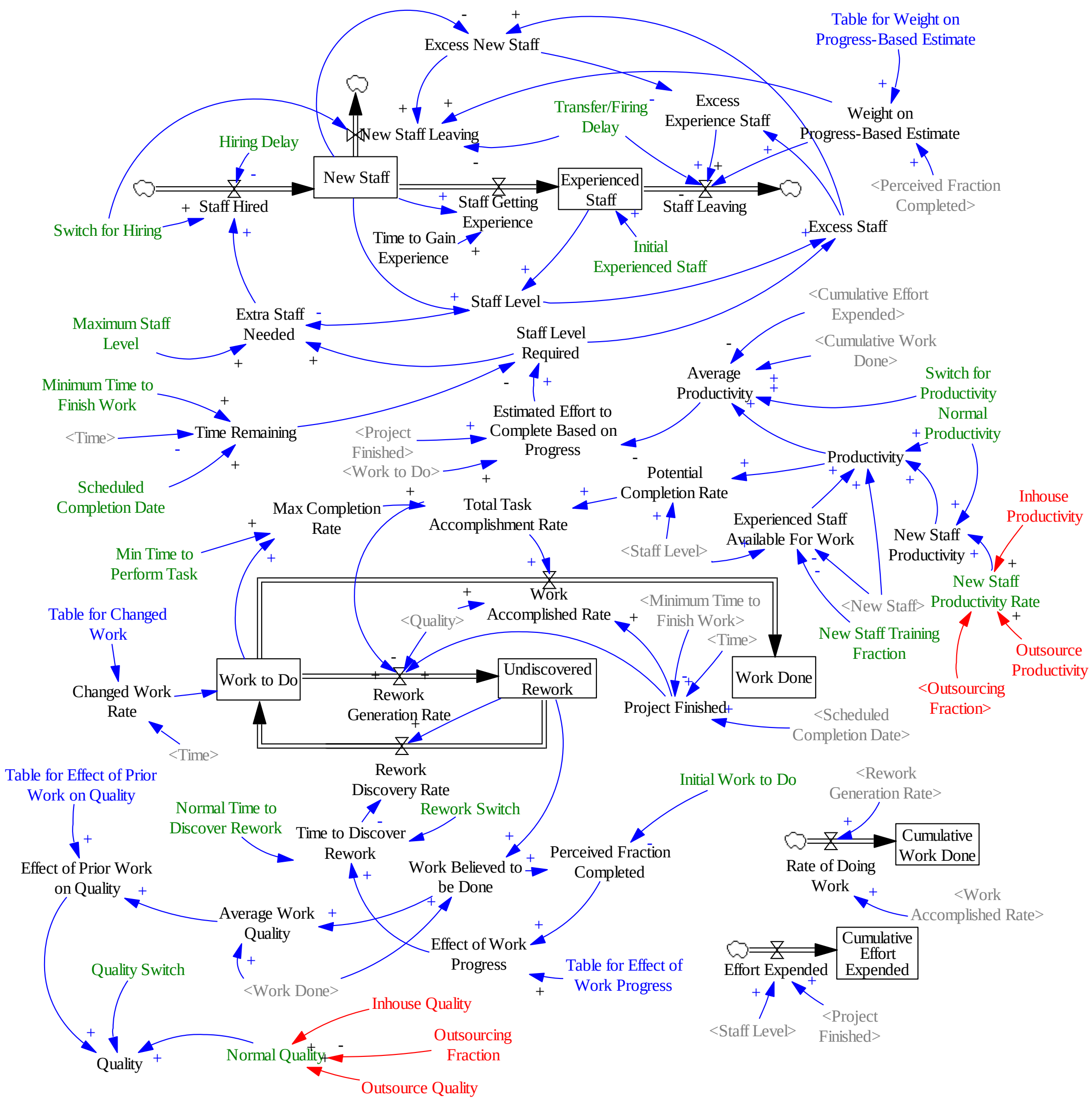

Figure 3: SD model for engineering resources

The results of running the above Vensim model to determine the labor effort to complete the engineering work based upon progress in a engineering project with a fixed completion date with varying degrees of outsourcing is shown below in Figure 4. It is shown that the 100% Outsourcing case always presents the greatest effort (cost) to complete the engineering work during any period during the project duration. It is also shown that, except in the In-house case, the outsourced engineering work completion date extends beyond the project scheduled completion date. This is caused by the quality, productivity, and associated learning curves of the outsourced craftsmen. Further study of the impact of these variables upon the project schedule will be performed as well as that of the initial engineering workload value of 8 tasks that was used in this study.

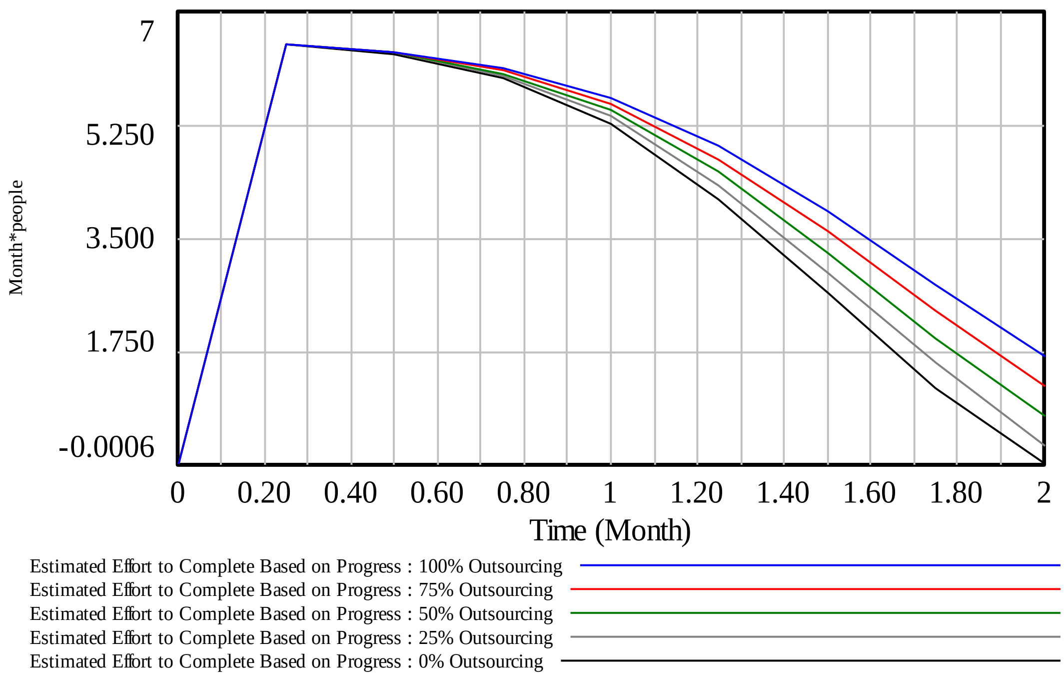

Figure 4: Estimated effort to complete based on progress in SD model

The engineering work completed during the project duration is presented in below Figure 5. Again, it is evident that it takes longer than 2 months to complete the initial work tasking when outsourcing engineering resources. Also, the case of 0% Outsourcing or total Insourcing would produce more engineering work done during the project than any combination of outsourcing/insourcing. This implies that management should concentrate on providing in-house engineering resources through the project completion.

The engineering staff level required by the project in order to accomplish the initial design tasks is shown in Figure 6. This table indicates that the In-house staffing case (0% Outsourcing) required less engineering staffing to complete the assigned tasks at scheduled project completion (Month 2). It also shows that all cases used less than the initial 6 engineers after Month 1 to complete the remaining engineering tasking during the project duration.

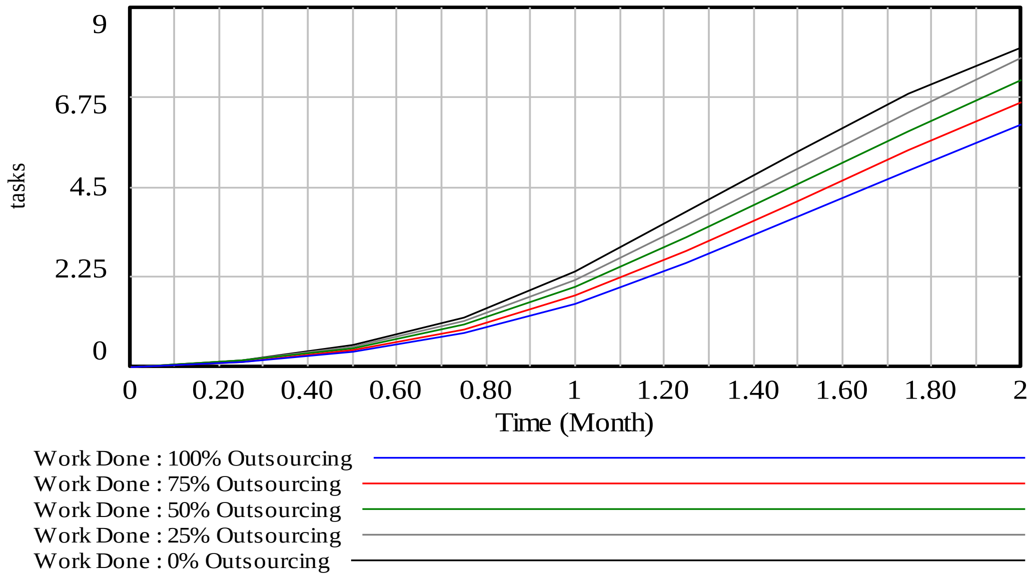

Figure 5: Engineering work done per percent of outsourcing

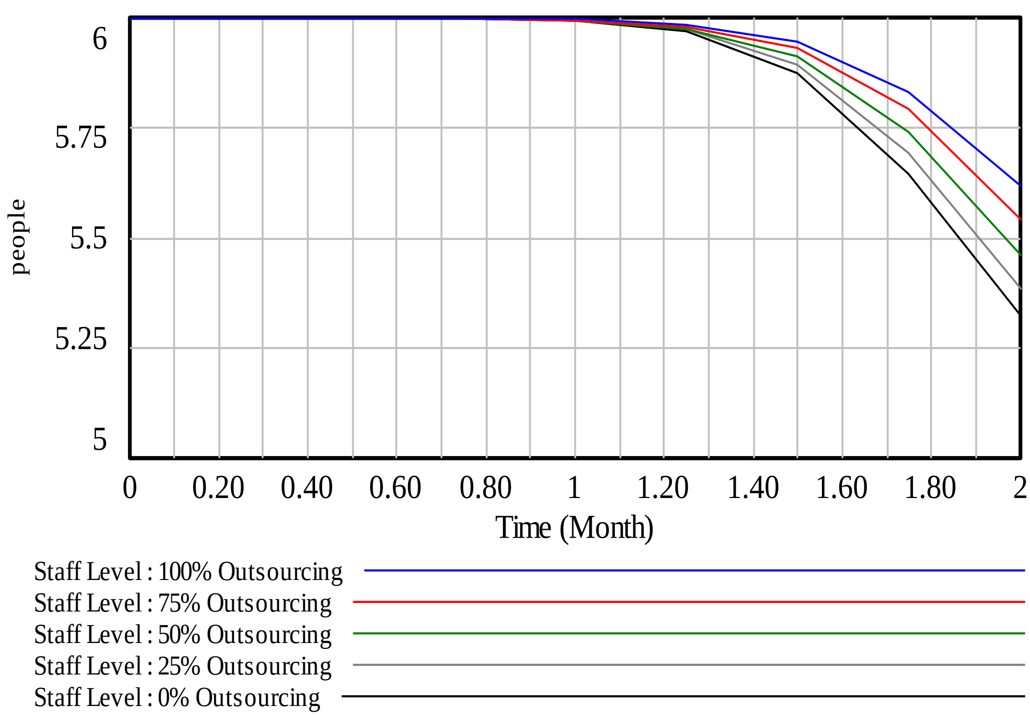

Figure 6: Engineering staff level per percent of outsourcing

The average productivity of the engineering staff is indicated in Table 1 as compared to a normal productivity value of 1. The table indicates that, for all cases, the average productivity of engineers climbs after project commencement to a value of 1. Also, the productivity for 0% Outsourcing (In-house) engineering started to decrease at the project completion date since all assigned engineering tasks were completed while all other cases were still performing the assigned engineering tasks.

Table 1:

Average Engineering Productivity

Time	Productivity per Outsourcing				
Month	**100%**	**75%**	**50%**	**25%**	**0%**
0	0	0	0	0	0
0.25	1.00	1.00	1.00	1.00	1.00
0.50	1.00	1.00	1.00	1.00	1.00
0.75	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00
1.25	1.00	1.00	1.00	1.00	1.00
1.50	1.00	1.00	1.00	1.00	1.00
1.75	1.00	1.00	1.00	1.00	1.00
2.00	1.00	1.00	1.00	1.00	0.98

The average engineering work quality increases during the project duration as is shown in Figure 7. As the project engineering staff gains more experience, the amount of engineering task rework diminishes. The graph indicates that the 0% Outsourcing produces the best overall average engineering work quality and approaches the ideal value of 1 earlier than all outsourcing cases. Also, the 75% and 100% Outsourcing cases do not achieve the value of 1 before the scheduled project completion date.

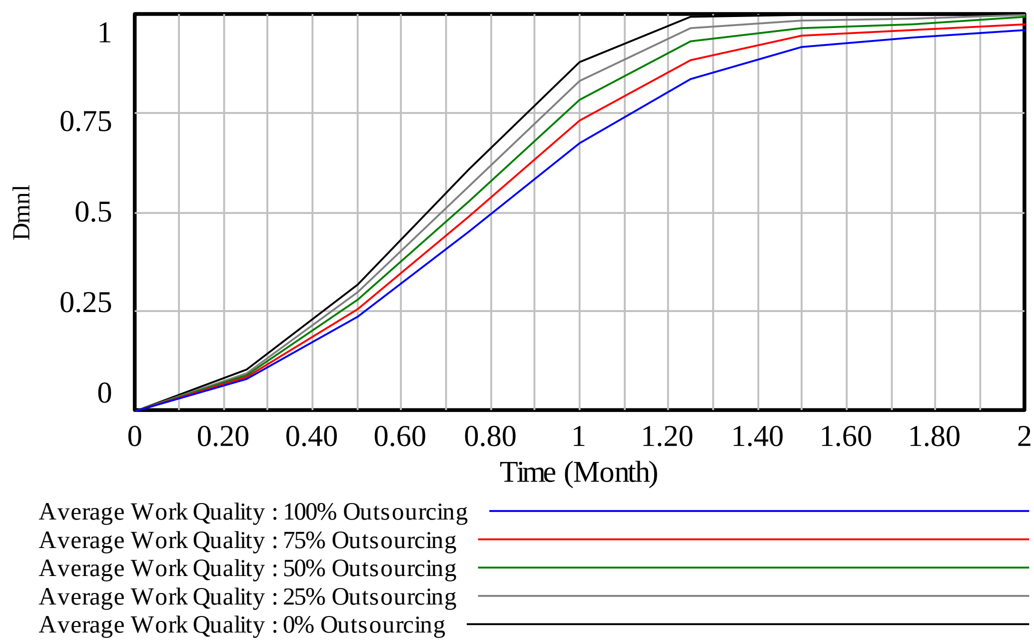

Figure 7: Average engineering work quality during project duration

Lastly, the SD model was validated/verified and compared with actual data from a $3.2 billion design-build project in the following section.

Model Validation

As mentioned, the system dynamics model was tested to understand its limitations and to improve it. Some model tests 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 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 engineering project cost estimates from a design-build project. 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 were also compared qualitatively for modes of behavior, shape of variables, asymmetries, relative amplitudes and phasing, and unusual events.

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 model were made to make the system perform better under changed/added work and changed scheduled completion dates, which reflected the project's operations.

Conclusion

There is a paucity of available literature on insourcing versus outsourcing engineering services on major shipbuilding and design-build projects. From the results of the literature review and the SD modeling variables, the engineering work output is dependent mainly upon the engineering quality, and to lesser extent the productivity and number of engineers. Accordingly, the decision to insource/outsource engineering work on projects may have significant cost (and time) impacts which should be considered by decision makers.

Comprehensive sensitivity analysis of various initial parameters, including: (1) initial number of experienced engineers assigned, (2) maximum number of engineers allowable, and (3) the initial number and duration of assigned engineering tasks will be performed in a future study. Additionally, the model will be modified to incorporate any changes to the scheduled project completion date and associated impacts to the project will be studied.

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Appendix

SD Model Variables

No.	Description	Units
(01)	Average Productivity=Switch for Productivity * ZIDZ(Cumulative Work Done, Cumulative Effort Expended) + (1-Switch for Productivity) * Productivity	tasks/(people*Month)
(02)	Average Work Quality=MIN(1,ZIDZ(Work Done , Work Believed to be Done))	Dmnl
(03)	Changed Work Rate=Table for Changed Work(Time)	tasks/Month
(04)	Cumulative Effort Expended= INTEG (Effort Expended,0)	people*Month
(05)	Cumulative Work Done= INTEG (Rate of Doing Work,0)	tasks
(06)	Effect of Prior Work on Quality=Table for Effect of Prior Work on Quality(Average Work Quality)	Dmnl
(07)	Effect of Work Progress=Table for Effect of Work Progress(Perceived Fraction Completed)	Dmnl
(08)	Effort Expended=IF THEN ELSE(Project Finished, 0, Staff Level)	people
(09)	Estimated Effort to Complete Based on Progress=IF THEN ELSE(Project Finished, 0, ZIDZ(Work to Do, Average Productivity))	people*Month
(10)	Excess Experience Staff=MAX(0, Excess Staff-Excess New Staff)	people
(11)	Excess New Staff=MAX(0, Excess Staff-New Staff)	people
(12)	Excess Staff=MAX(0, Staff Level-Staff Level Required)	people
(13)	Experienced Staff= INTEG (Staff Getting Experience-Staff Leaving, Initial Experienced Staff)	people
(14)	Experienced Staff Available For Work=Staff Level-New Staff-New Staff Training Fraction*New Staff	people
(15)	Extra Staff Needed=MIN(Maximum Staff Level, MAX(0, Staff Level Required-Staff Level))	people
(16)	FINAL TIME = 2.25	Month
(17)	Hiring Delay=0.25	Month
(18)	Inhouse Productivity=1	Dmnl
(19)	Inhouse Quality=1	Dmnl
(20)	Initial Experienced Staff=6	people
(21)	INITIAL TIME = 0	Month
(22)	Initial Work to Do=8	tasks
(23)	Max Completion Rate=Work to Do/Min Time to Perform Task	tasks/Month
(24)	Maximum Staff Level=10	people
(25)	Min Time to Perform Task=0.25	Month
(26)	Minimum Time to Finish Work=1.5	Month
(27)	New Staff= INTEG (Staff Hired-New Staff Leaving-Staff Getting Experience,0)	people
(28)	New Staff Leaving="Weight on Progress-Based Estimate"*Excess New Staff*"Transfer/Firing Delay"*Switch for Hiring	people/Month
(29)	New Staff Productivity=New Staff Productivity Rate*Normal Productivity	tasks/(Month*people)
(30)	New Staff Productivity Rate=Inhouse Productivity*(1-Outsourcing Fraction)+ Outsource Productivity*Outsourcing Fraction	Dmnl
(31)	New Staff Training Fraction=0.5	Dmnl
(32)	Normal Productivity=1	tasks/(Month*people)
(33)	Normal Quality=Inhouse Quality*(1-Outsourcing Fraction)+Outsource Quality*Outsourcing Fraction	Dmnl

(34)	Normal Time to Discover Rework=0.25	Month
(35)	Outsource Productivity=0.85	Dmnl
(36)	Outsource Quality=0.8	Dmnl
(37)	Outsourcing Fraction=1	Dmnl
(38)	Perceived Fraction Completed=MIN(1,ZIDZ(Work Believed to be Done, Initial Work to Do))	Dmnl
(39)	Potential Completion Rate=Staff Level*Productivity	tasks/Month
(40)	Productivity=(New Staff*New Staff Productivity+Experienced Staff Available For Work*Normal Productivity)/(New Staff+Experienced Staff Available For Work)	tasks/people/Month
(41)	Project Finished=IF THEN ELSE(Scheduled Completion Date+Minimum Time to Finish Work-Time<=0, 1, 0)	Dmnl
(42)	Quality=Quality Switch * Normal Quality * Effect of Prior Work on Quality + (1-Quality Switch) * Normal Quality	Dmnl
(43)	Quality Switch=1	Dmnl
(44)	Rate of Doing Work=Rework Generation Rate+Work Accomplished Rate	tasks/Month
(45)	Rework Discovery Rate=Undiscovered Rework/Time to Discover Rework	tasks/Month
(46)	Rework Generation Rate=IF THEN ELSE(Project Finished, 0 , Total Task Accomplishment Rate*(1-Quality))	tasks/Month
(47)	Rework Switch=1	Dmnl
(48)	SAVEPER = TIME STEP	Month
(49)	Scheduled Completion Date=2	Month
(50)	Staff Getting Experience=MAX(0, New Staff/Time to Gain Experience)	people/Month
(51)	Staff Hired=MAX(0, (Extra Staff Needed/Hiring Delay)*Switch for Hiring)	people/Month
(52)	Staff Leaving=Excess Experience Staff*"Weight on Progress-Based Estimate"*"Transfer/Firing Delay"	people/Month
(53)	Staff Level=MAX(0, Experienced Staff+New Staff)	people
(54)	Level Required=Estimated Effort to Complete Based on Progress/Time Remaining	people
(55)	Switch for Hiring=1	Dmnl
(56)	Switch for Productivity=1	Dmnl
(57)	Table for Changed Work([(0,0)-(2.5,0)],(0,0),(1,0),(2.5,0))	Dmnl
(58)	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))	Dmnl
(59)	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))	Dmnl
(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))	Dmnl
(61)	Time Remaining=MAX(Minimum Time to Finish Work, Scheduled Completion Date-Time)	Month
(62)	TIME STEP = 0.25	Month
(63)	Time to Discover Rework=Rework Switch * Normal Time to Discover Rework* Effect of Work Progress + (1 - Rework Switch) * Normal Time to Discover Rework	Month
(64)	Time to Gain Experience=2	Month
(65)	Total Task Accomplishment Rate=MAX(0,MIN(Max Completion Rate, Potential Completion Rate))	tasks/Month
(66)	"Transfer/Firing Delay"=0.25	1/Month
(67)	Undiscovered Rework= INTEG (Rework Generation Rate-Rework Discovery Rate,0)	tasks
(68)	"Weight on Progress-Based Estimate"="Table for Weight on Progress-Based Estimate"(Perceived Fraction Completed)	Dmnl
(69)	Work Accomplished Rate=IF THEN ELSE(Project Finished, 0, Total Task Accomplishment Rate*Quality)	tasks/Month
(70)	Work Believed to be Done=Undiscovered Rework+Work Done	tasks

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(71)	Work Done= INTEG (Work Accomplished Rate,0)	tasks
(72)	Work to Do= INTEG (Rework Discovery Rate-Rework Generation Rate-Work Accomplished Rate+Changed Work Rate,Initial Work to Do)	tasks