Improving the Naval Construction Process Through Lean Implementation

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Abstract

This study uses systems dynamics modeling to analyze the United States Navy's current construction administration process from design to implementation in order to recommend process improvements, which will prevent cost overruns, delays, and ultimately a waste of tax payers' resources. This study specifically examines the impact of upstream design implementations on the entire system, and incorporates a number of lean thinking ideas. It demonstrates the positive effects of increased constructability efforts and design sharing among engineers, and indicates that when limited resources exist it is best to focus constructability and design sharing efforts as early as possible during the upstream process. Finally, this paper concludes with a number of recommendations for how the United States Navy's Civil Engineer Corps and possibly Seabee Construction Battalions can best implement these ideas.

Introduction

Delays and cost overruns are the rule rather than the exception in both the governmental and private construction industries. Design changes due to lack of constructability become necessary late in the construction phase, generating costly ripple effects which create delay and disruption throughout the entire organization. In the increasingly competitive building construction industry, there is an increasing demand for many companies to decrease costs and to do more with less. Consequently, a revitalized effort is emerging to develop new methods and tools, in which the design for quality, cost, constructability and reliability play an important role. As part of this effort, many private construction companies, as well as the U.S. Department of Defense and the U.S. Navy, are looking at how lean thinking initiatives from manufacturing and other industries might be applied to help improve the construction process.

The planning and management of building design has historically focused upon traditional methods of planning such as Critical Path Method (CPM). Little effort is made to understand the complexities of the design process; instead design managers focus on allocating work packages where the planned output is a set of deliverables. This current design method forces design teams to manage their work on a discipline basis, each working on achieving their deliverable as dictated by the design program with little regard for the relationship with other disciplines and organizations. In addition, because architect and engineering firms normally view design and construction as two separate and completely independent phases of work for the project, it makes it difficult to verify constructability in a design and create flow in the overall process.

This study helps by first developing an exploratory System Dynamics model to better understand the intricacies of the often over-complicated construction design and implementation process. It then runs a number of simulations to study how improved design sharing and increased constructability impact the system. Next, it simulates a number of scenarios where resources are significantly constrained in order to see where and when these limited resources should be used in order to optimize the construction process. The results of these simulations show that increased design sharing and constructability efforts significantly decrease costs and results in significantly faster project completion times. Most importantly, the results also suggest that it is significantly better to focus these efforts early in the design process rather than later once much of the construction phase has already begun. This study concludes with a number of suggestions on how the U.S. Navy can best implement these ideas into the Naval Civil Engineer Corps and its Seabee Construction Battalions. Finally, a broader objective of this study is to promote the applicability of System Dynamics towards solving various organizational challenges faced by the Navy.

Background and Context

Just as the industrial revolution and its mass production methodology led to wasteful practices in the manufacturing industry during the early and mid-20th Century, the construction industry was also plagued by inefficiency, a problem that continues until this day. But while the development of Total Quality Management and eventually Lean Thinking Principles began to revolutionize manufacturing in the late 20th Century, the construction industry has yet to fully embrace a similar line of thinking. Yet the need to do so is quite apparent. Quality costs are perhaps the greatest area of waste. In numerous studies from different countries, the cost of poor quality (non conformance), as measured on site, has turned out to be 10-20% of total project costs.[1] In an American study of several industrial projects, deviation costs averaged 12.4% of the total installed project costs, however, "this value is only the tip of the iceberg".[2]

The causes of these quality problems are attributed to

- design 78%
- construction 17%
- material supply 5%

Thus, quality problems are considerable in all phases of construction. But as the statistics show, design is often the source of greatest quality problems.

Maximizing value and minimizing waste at the project level is difficult when the contractual structures inhibit coordination, stifle cooperation and innovation, and rewards individual contractors for both reserving good ideas, and optimizing their performance at the expense of others. What is wrong? What is standing in the way of their being able to work as a true team; one able to work together to maximize value while minimizing waste throughout the process?

In the pursuit of answers to these questions, a consortium of design professional and construction practitioners met for five years to determine if there might not be a better way to organize themselves to deliver a project.[3] Their research led them to four major systemic problems with the traditional contractual approach. The four problems with a brief explanation are as follows:

Problem 1: Good ideas are held back

The Mechanical, Electrical and Pluming contractor and other major trades were generally brought into the process by the General Contractor (GC) once the drawings were at the design development stage in order to establish a competitive price. Even though the trades were frequently consulted through the design process, there was no real commitment to or from them because a number of different companies representing the same trades were involved. As a result, each of the trade contractors saved their best ideas in hopes of gaining a competitive edge during the "bidding process." Many times these ideas were very good. Time and opportunity for innovation were lost as the design team attempted to revamp their designs to accommodate the best of these late arriving ideas.

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[1] Cnuddle, M. 1991. Lack of quality in construction – economic losses, European Symposium on Management, Proceedings, pp. 508-515.
[2] Burati, James L., Mathews, Michael F. & Kalidindi, S.N. 1991. Quality Management in Construction Industry. Journal of construction Engineering and Management, Vol 117, No.2, pp 341-359
[3] Matthews, Owen and Howell, Gregory, Integrated Project Delivery An Example of Relational Contracting, Lean Construction Journal 2005, p 46-61.

Problem 2: Contracting limits cooperation and innovation

A systemic, but less obvious problem was the system of subcontracts that link the trades and form the framework for the relationships on the project. The price contactor held the contract for every consultant and subcontractor. Long and tedious subcontract agreements attempted to spell out in great detail exactly what each subcontractor was to provide, rules for compensation, and sometimes useful, if unrealistic, information about when work was to be performed. These long subcontracts mostly dealt with remedies and penalties for non compliance. These contracts made it difficult to innovate across trade boundaries even though the work itself was frequently interdependent.

Problem 3: Inability to coordinate

While some projects held "partnering" sessions, there was no formal effort to link the planning systems of the various subcontractors, or to form any mutual commitment or expectations amongst them.

Problem 4: The pressure for local optimization

Each subcontractor fights to optimize his performance because no one else will take care of him. The subcontractor agreement and the inability to coordinate between sub-contractors drives subcontractors to defend their turf at the expense of both the client and other subcontractors. Traditional subcontracting agreements entice subcontractors to take a legalistic and litigious stance, making optimization impossible.

With these ominous challenges confronting the construction industry, perhaps lean thinking provides some keys to potential solutions. Indeed, lean concepts such as value, flow, pull and perfection can be applied in analyzing the current construction process and perhaps used to help eliminate wasteful practices. This study specifically focuses on the concepts of flow and perfection in both the design and construction phases of the process. It looks at how to increase constructability through enhanced client-general contractor interaction and by improved interaction between the general contractor and sub contractors. It also examines how improved design sharing of engineers within the general contracting firm can help to eliminate errors in the design process.

System Dynamics Modeling

Because of the complexity of the construction process and its inherent non-linear relationships between different phases, actors, and resources; System Dynamics serves as an excellent tool for helping to better understand this system. It is important to point out that construction projects are essentially human enterprises, and cannot be understood solely in terms of technical relations among components. Most of the data required to understand the evolution and dynamics needed to determine the variables that cause rework are concerned primarily with managerial decision-

making and sometimes called “soft” variables, which contribute to the complex nature of the problem at hand.[4]
Typically rework originates in the design stage of a project.[5] Therefore the System Dynamics model focuses on modeling and analyzing those factors that influence its occurrence during the design process. The model consists of three parts:

1) Task Flow in Construction Design
2) Factors Contributing to Design Error
3) Financial Impacts of the System

Below is the “Task Flow in Construction Design” segment of the model, which represents the flow of tasks in construction design.[6]

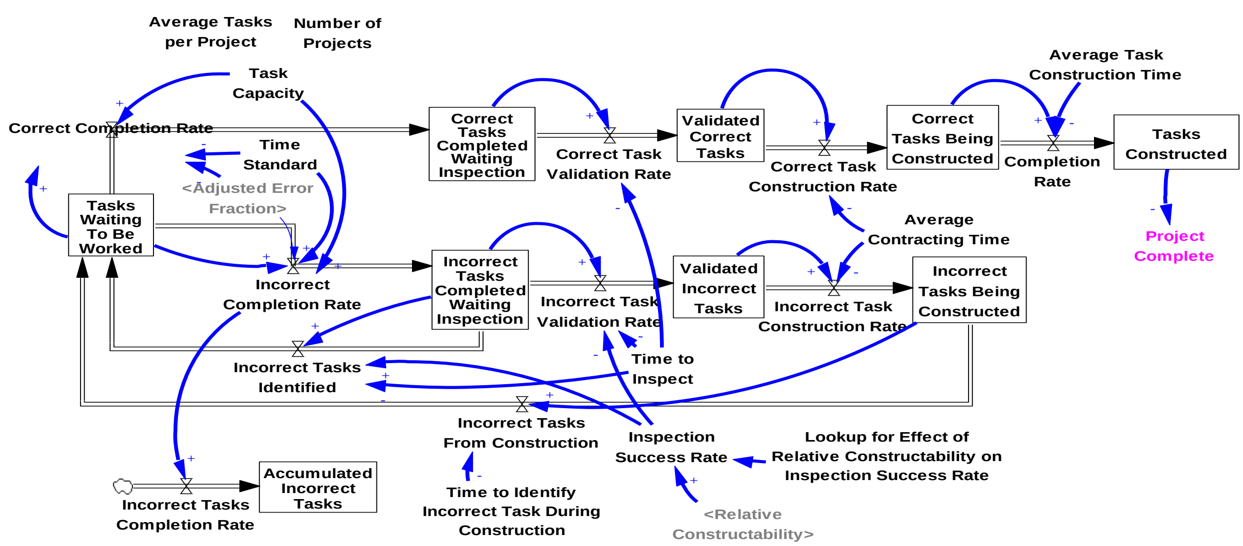


Figure 1: System Dynamics Model- Task Flow in Construction Design

Process of designing tasks

The variable Tasks Waiting to be Worked represents the total number of tasks that must be completed by the General Contractor (GC) for a typical construction project. The Task Capacity and Adjusted Error Fraction regulate how fast the GC can complete the design of various tasks, and what ratio of them are completed correctly or incorrectly. Correctly completed tasks follow along the pipeline at top; they are inspected for correctness, validated, and then are sent to the construction site to be built. Incorrectly designed tasks follow along the bottom pipeline; they are inspected for accuracy, which is governed by the Inspection Success Rate. If an Incorrectly Designed Task is caught in the Validation Phase, it then returns immediately to the Tasks Waiting to be Worked for rework. If not, the incorrect task is sent to the construction site to be

[4] Sterman,J.D. (1992) Systems Dynamic Modeling for Project Management, Working Paper, Systems Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA
[5] Burati et al., 1992 Causes of quality deviation in design and construction, ASCE Journal of Construction Engineering and Management, 118 (1), 34-49
[6] Contact the author for a full Vensim version of this model. The document reference can be found in Appendix B.

built and the error is not found for several weeks. This is an important delay in the system, as not only is time wasted trying to build the incorrectly designed task, but there is an additional delay as arbitration and sometimes legal proceeding unwind between the GC and the Sub-Contractor.

The second segment of the System Dynamics Model “Factors Contributing to Design Errors” is shown below.

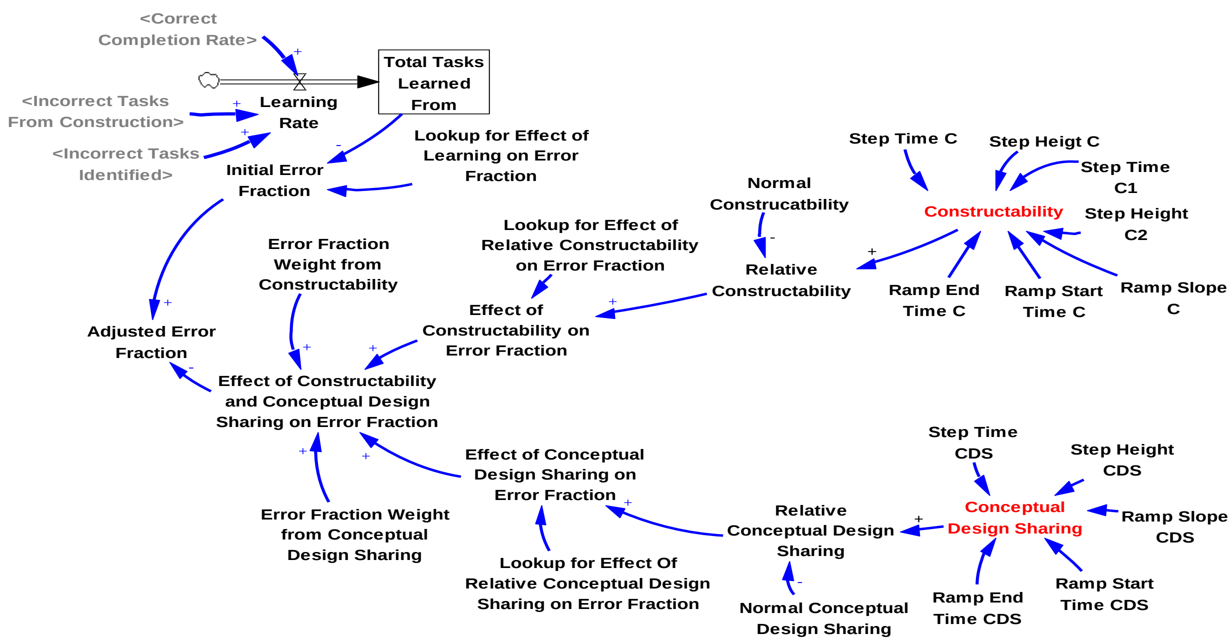
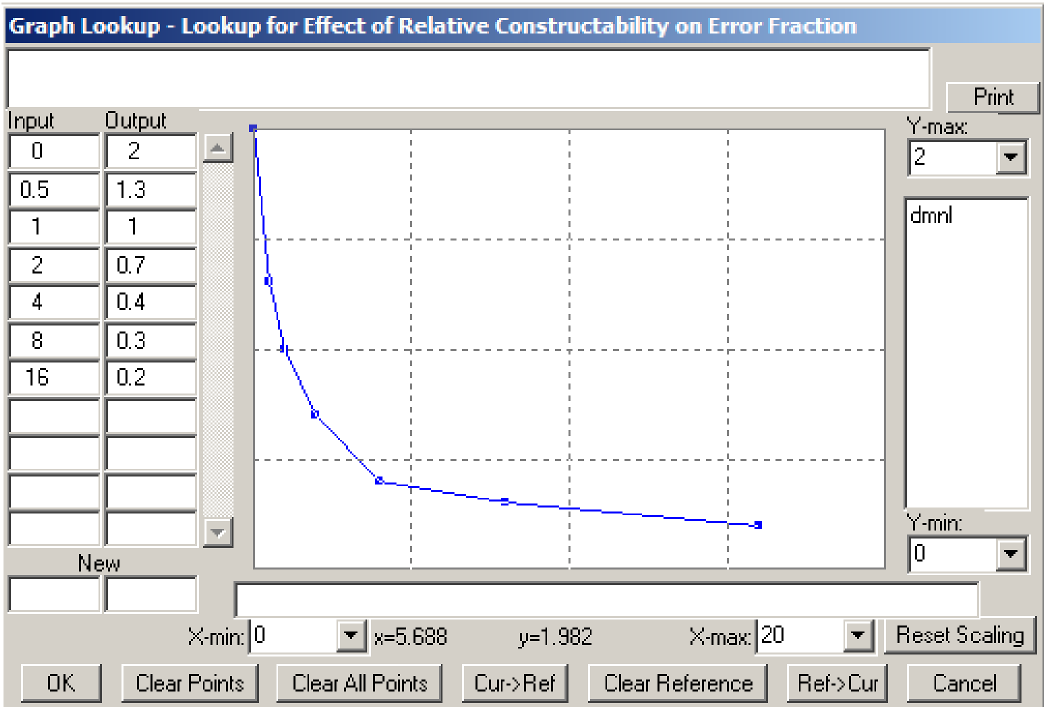


Figure 2: System Dynamics Model- Factors Contributing to Design Error

<u>Error fraction in design</u>

Conceptually, the error fraction for this study is determined by three components: Learning, Constructability and Design Sharing. The Adjusted Error Fraction in the model is determined by the product of the Effect of Constructability and Design Sharing on Error Fraction and Initial Error Fraction. The Effect of Constructability and Design Sharing on Error Fraction is determined by the effect each exogenous variable has on error fraction and its corresponding Error Fraction Weight (Constructability - .78 and Design Sharing - .22).

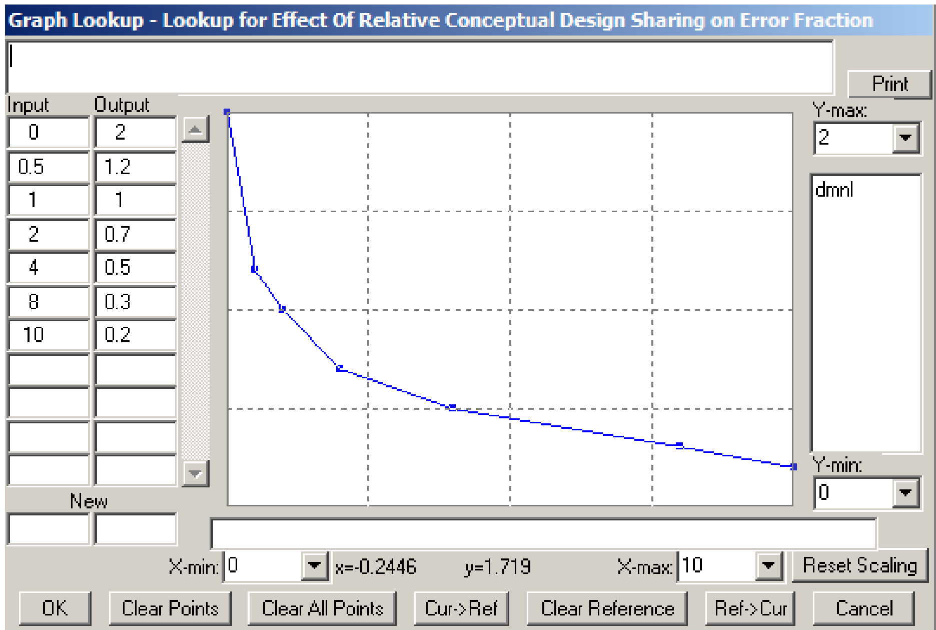
Constructability and Design Sharing are two exogenous variables that make up the Effect of Constructability and Design Sharing on Error Fraction. The Effect of Constructability on Error Fraction is determined by the Relative Constructability and the Lookup for Effect of Relative Construability on Error Fraction. Relative Constructability is composed of the Normal Constructability (.25) and the exogenous variable Constructability. Below in Figure 3 is the table lookup that the model uses to determine the output value for the Lookup for Effect of Constructability on Error Fraction; which follows the logic that “The more time spent conducting constructability reviews, the lower the effect of relative constructability on error fraction.”



The table and graph represent the relationship between the amount of time a firm dedicates to constructability and the effect on error fraction. As more time is dedicated to constructability, the error fraction is reduced.

Figure 3: Look up for Effect of Relative Constructability on Error Fraction

Like Constructability, the Effect of Design Sharing on Error Fraction is determined by a relative value and a table lookup. Relative Sharing is derived from the Normal Design Sharing (.10) and the variable Design Sharing, which can also be exogenously adjusted for various simulations. Currently, design teams normally meet 3 times after the conceptual design to share design changes. These meeting occur around the 30%, 60% and 90% design stages. Although in theory Design Sharing could be measured in terms of number of meetings, this is only one aspect of design sharing and is used as a rough measure to gauge the amount of design sharing inside an organization. Therefore, for the purpose of this study Design Sharing is a dimensionless variable, since Design Sharing includes other important factors such as informal meetings, and e-mail and lunchtime discussions amongst engineers. The table lookup that represents the relationship between the amount of design sharing and error fraction can be seen in Figure 4 below.



The table and graph represent the relationship between the amount of time a firm dedicates to design sharing and the effect on error fraction. As the more time is dedicated to design sharing, the error fraction is reduced.

Figure 4: Look up for Effect of Relative Design Sharing on Error Fraction

Initial Error Fraction

The Initial Error Fraction is another key variable that impacts Adjusted Error Fraction. Figure 5 below shows the portion of the System Dynamics model that represents the impact that the Learning Rate and Total Tasks Learned From affect the Initial Error Fraction.

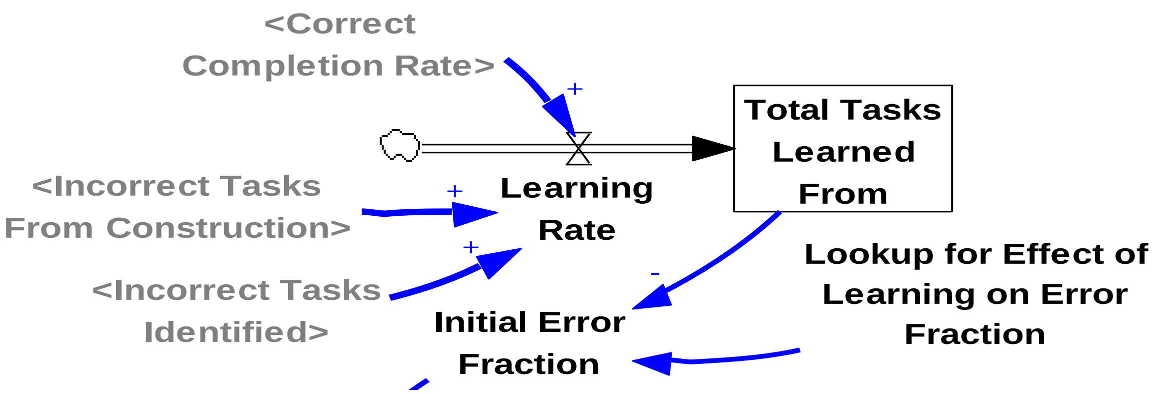
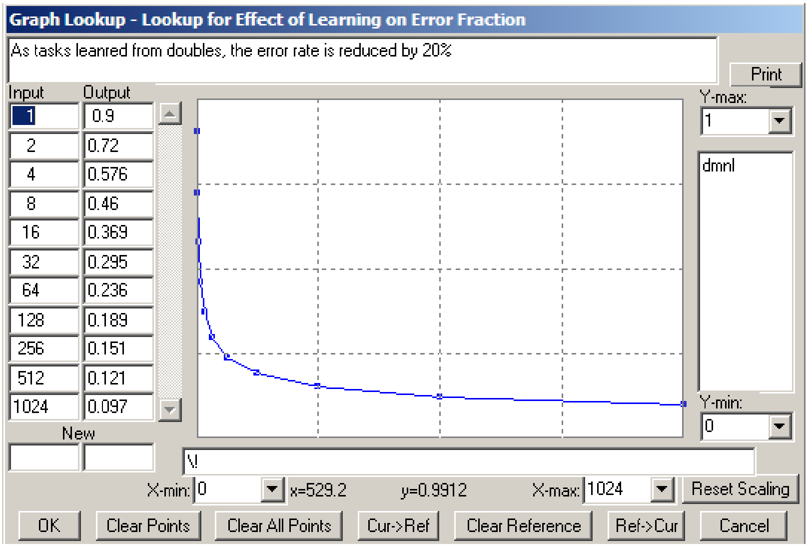


Figure 5: System Dynamics Model- Initial Error Fraction

The Initial Error Fraction is determined by the Total Tasks Learned From (the number of tasks that Architecting & Engineering (A&E) learns from –experience) and the Lookup for Effect of Learning on Error Fraction. The accumulation of the Total Tasks Learned From is made up of the sum of incorrect tasks from construction, incorrect tasks identified and the correct completion rate. Below is the lookup table (Figure 6) that represents the correlation between the number of tasks learned and the error fraction.



The table and graph represent a relationship between the Total Tasks Learned From and Initial Error Fraction.. As the number of tasks learned from doubles, the error rate decreases by 20%.

Figure 6: Lookup for Effect of Learning on Error Fraction Graph and Table.

The following section introduces the final segment of the model, "Financial Impacts of the System" (See Figure 7 below). This section of the model is fairly intuitive. It adds up the total number of Design Iterations (both correct and incorrect, where the number of incorrect tasks represents re-work), Total Inspections, and Total Construction Activities (abbreviated as Total Activities) as well as their associated costs and produces a final variable called Total Project Cost which allows us to see the total cost of a given project for a specific simulation.

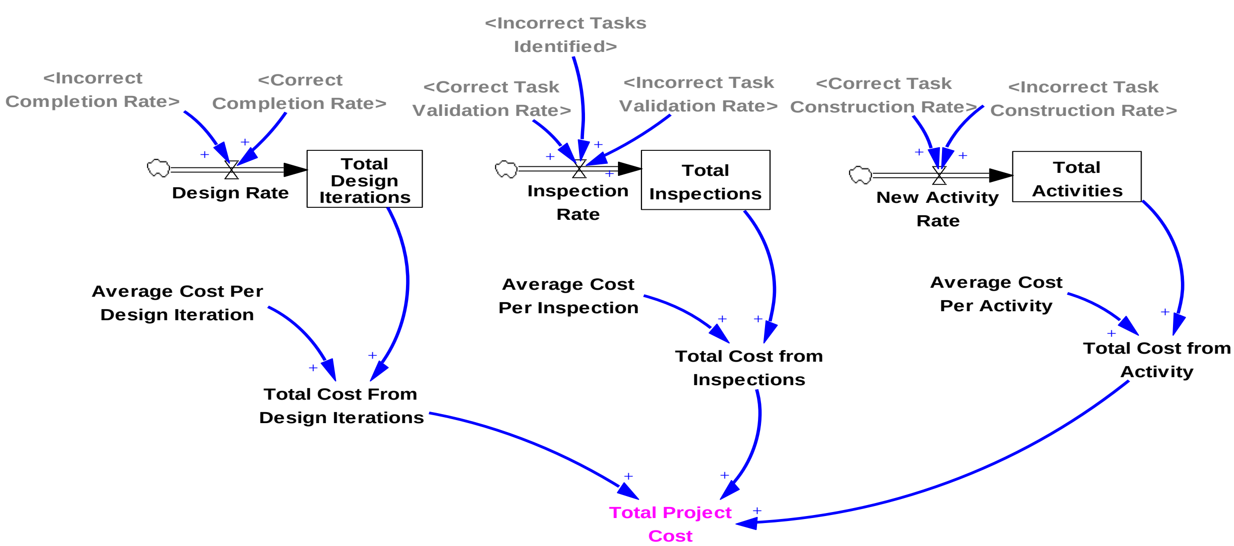


Figure 7: System Dynamics Model: Financial Impacts of the System

Simulation Results

This study used two different approaches to simulation. First, it included a one-variable-at-a-time approach where only one exogenous variable was changed at a time to determine the full range of implications that change will have on different internal variables in the model. Once this was completed, a two-variable-at-a-time approach was used to better understand the dynamic interaction of both constructability and design sharing on the system. The results were then compared to the current state of construction design as it is generally understood, allowing conclusions and recommendations to be drawn.

Effects of Constructability

The first simulation was performed to determine whether early or late constructability in a project (assuming resource limitations only allowed for a total of 20 weeks of full constructability) would produce the greatest benefits for the system. Current Constructability in equilibrium is set at .25 (2 hrs/wk) for the life of the project. For this test, Constructability was set to 2 (16hrs/wk) from 0 to 20 weeks in the "Early Constructability" simulation, then back to .25 until the end of the project. Similarly, Constructability was set to .25 (2hrs/wk) until weeks 50 to 70 in the "Late Constructability" simulation, when it was raised to 2 (16 hrs/wk) and then back down to .25 until the end of the project. It is important to note that the total constructability effort over time was equal in both simulations, and therefore the results of the simulation are not skewed by numerical sensitivity. The following graph shows how constructability was changed to represent early and late constructability.

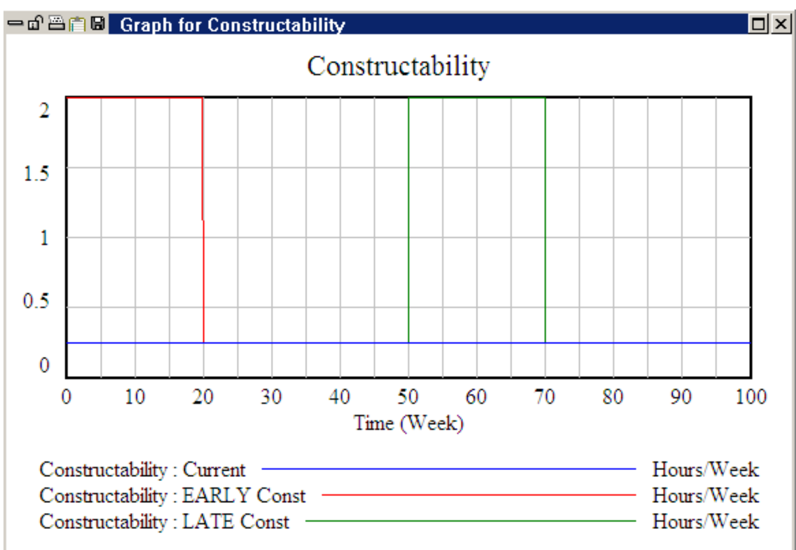


Figure 8: Constructability Inputs

Next, the graphs in Figures 9 and 10 show the effect of early and late constructability on Adjusted Error Fraction and on Incorrect Tasks Being Constructed. A quick look at these graphs shows that there is a greater total impact on the Adjusted Error Fraction when Early Constructability is used as opposed to late constructability. The graph of Incorrect Tasks Being Constructed (Figure 10) shows that the total number of incorrect tasks drops significantly when

Early Constructability is conducted as opposed to late constructability. In addition, it shows that late constructability has very little positive impact on the system when compared to the equilibrium scenario. Nevertheless, because of the nonlinearities and delays in the design process, it alone does not necessarily mean that Early Constructability is better than late constructability.

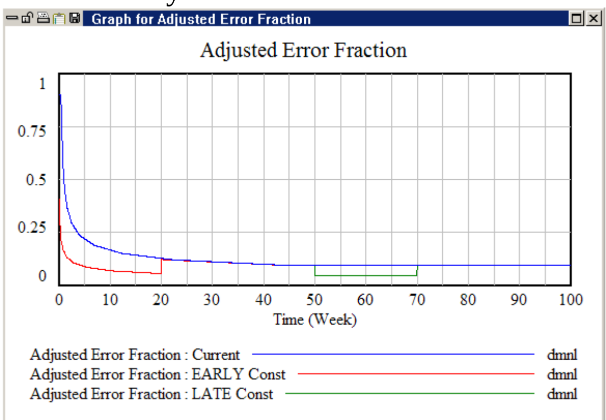


Figure 9: Adjusted Error Fraction

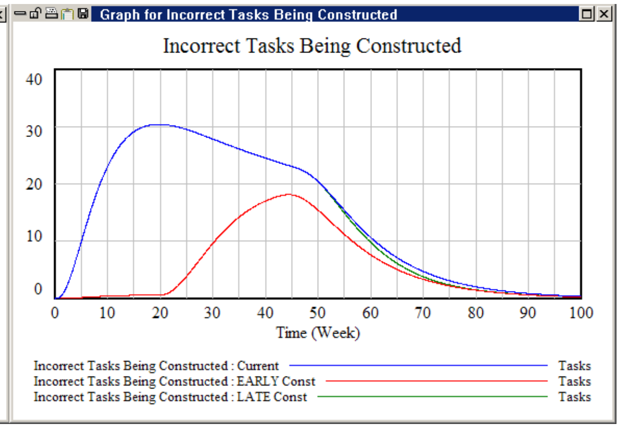


Figure 10: Incorrect Tasks Being Constructed

Finally, Figures 11 and 12 below show how the Project Completion Date and Total Project Costs are impacted. The project completion is approximately 4 weeks shorter when Early Constructability is performed as opposed to the equilibrium or current constructability scenario. When late constructability is performed, the project completion is approximately 1.5 weeks shorter than current constructability. Thus, the model suggests that Early Constructability has the potential to provide greater benefits with regards to time savings over late constructability by a ratio of 4:1.5, over a 100% advantage.

Similarly, the total project costs are reduced by approximately 9% when Early Constructability is performed, while a meager cost savings of less than .5% is provided by Late constructability. Therefore, while a constant high level of constructability is desired throughout the entire project, when only limited resources are available which is almost always the case, Early Constructability is clearly superior to Late constructability with regards to both Project Cost and Project Completion Time.

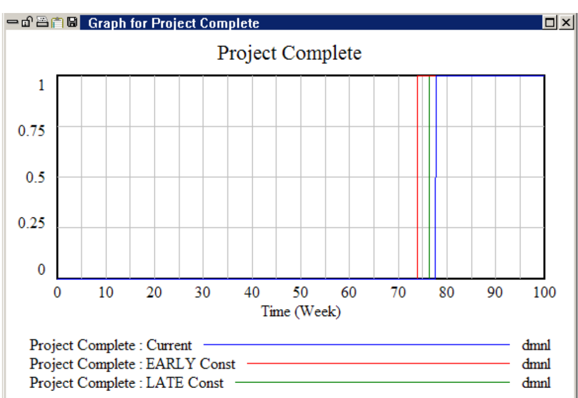


Figure 11: Project Completion Time

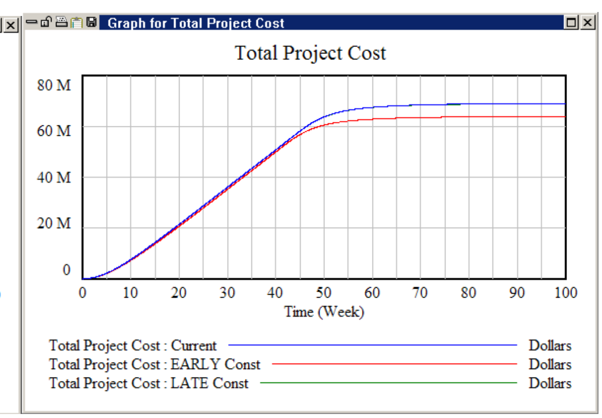


Figure 12: Total Project Cost

Effects of Design Sharing

The second exogenous variable, Design Sharing, was manipulated by increasing the value from .1, which represents traditional design sharing at the 30, 60 and 90% design stages, to .4 representing an increased level of iterative design sharing throughout the design process. The graph below shows the inputs to the model, the equilibrium case is shown in blue and the improved design sharing scenario is in red.

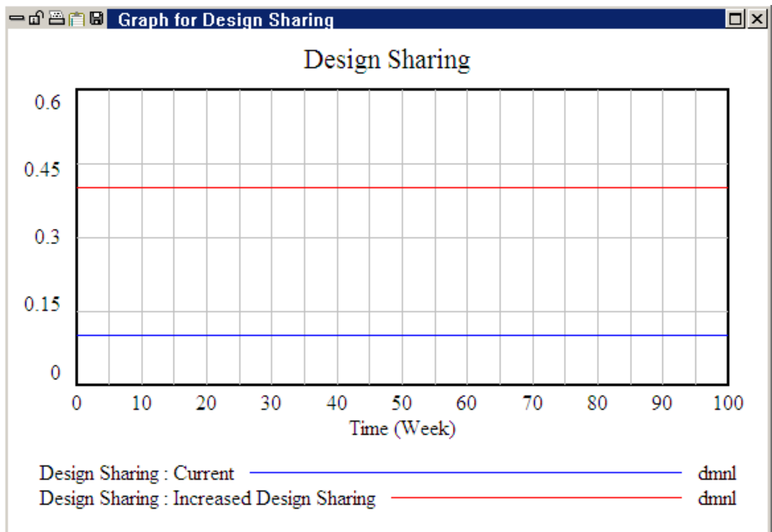
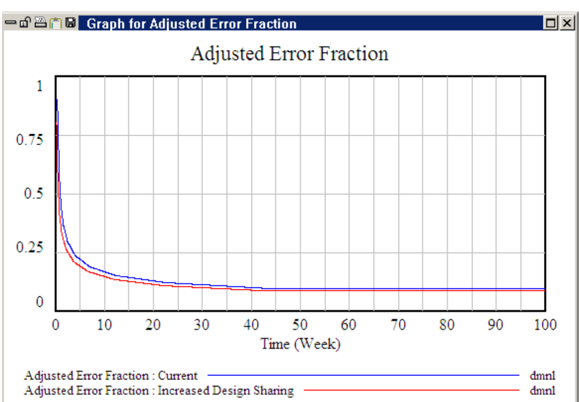


Figure 13: Design Sharing

Figures 14 and 15 below (Adjusted Error Fraction and Incorrect Tasks Waiting Inspection) show only a marginal decrease in both graphs from increased Design Sharing as compared to the equilibrium scenario. However, the graph of Incorrect Tasks Being Constructed (Figure 16) shows a more significant decrease in the total number of Incorrect Tasks Being Constructed.



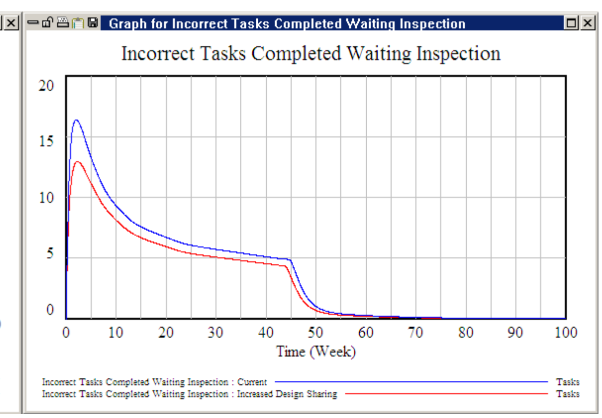


Figure 14: Adjusted Error Fraction **Figure 15: Incorrect Tasks Waiting Inspection**

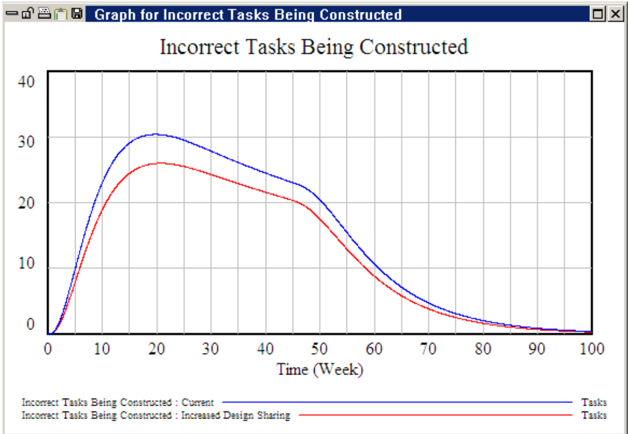


Figure 16: Incorrect Tasks Being Constructed

Nevertheless, as the Project Completion Date (abbreviated Project Complete) and Total Project Cost graphs show below, improved design sharing produces a reduction in project completion by approximately 2.5 weeks. Similarly, Total Project Costs were reduced by approximately 2%.

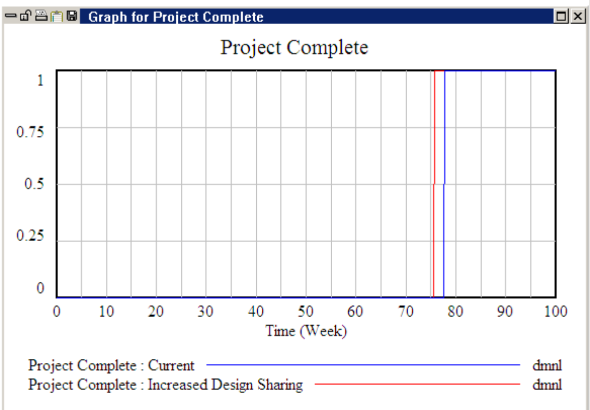


Figure 17: Project Completion Time

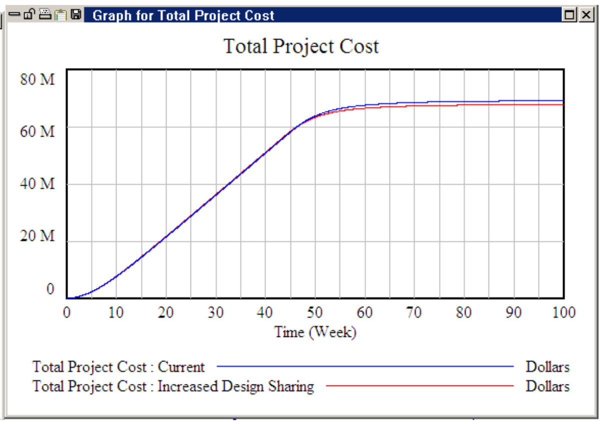


Figure 18: Total Project Cost

Combined Effect of Constructability and Design Sharing

After using the one-at-a-time method for manipulating the exogenous variables Constructability and Design Sharing, both exogenous variables were manipulated at the same time. Constructability was set to 2 which represents 16hrs/wk for the entire life of the project. Design Sharing was set to 1 which represents a continual design sharing for the life of the project. The following two graphs represent the changes in both exogenous variables.

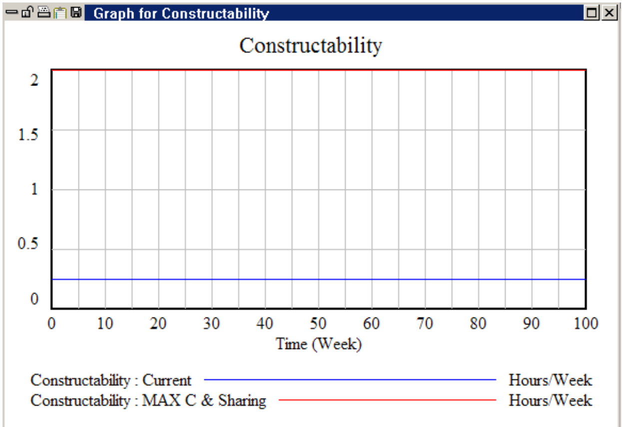


Figure 19: Constructability

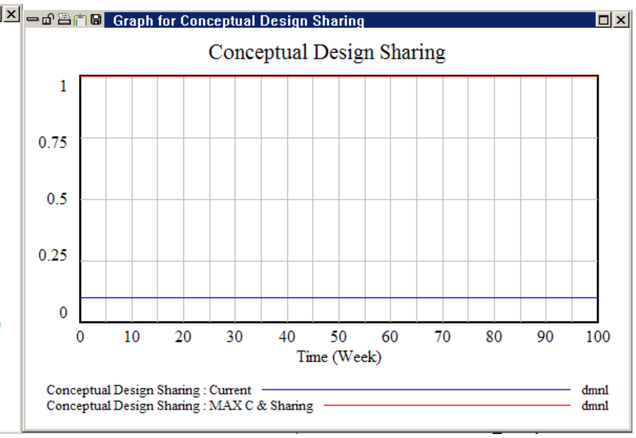


Figure 20: Conceptual Design Sharing

Next, the following four graphs show the positive impact that having maximum constructability and design sharing have on a construction project. This represents the maximum or ideal benefits that can be gained by improvements in these two areas. As expected, the Adjusted Error Fraction was drastically reduced for the entire life of the project leading to a significant reduction in Incorrect Tasks Being Constructed. Having less Incorrect Tasks Being Constructed reduced the total project completion by approximately 10 weeks and a Total Project Costs savings of approximately 14 % ($10M).

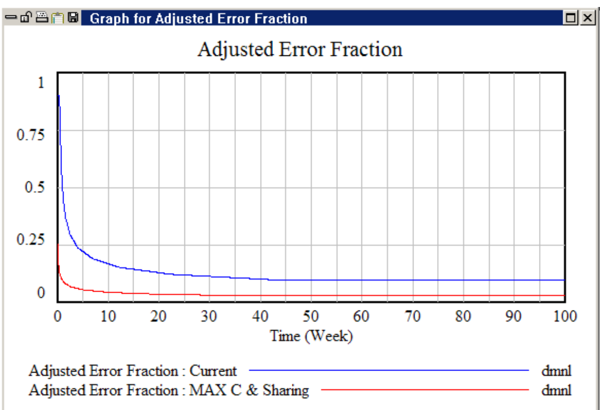


Figure 21: Adjusted Error Fraction

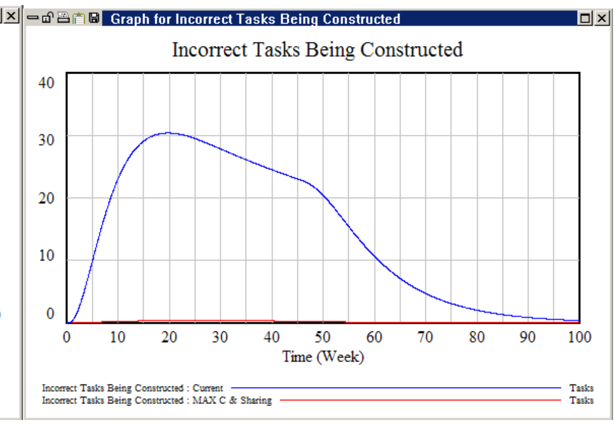


Figure 22: Incorrect Tasks Being Constructed

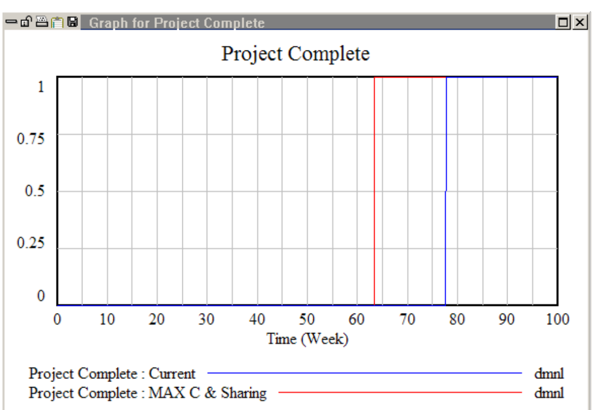


Figure 23: Project Completion Time

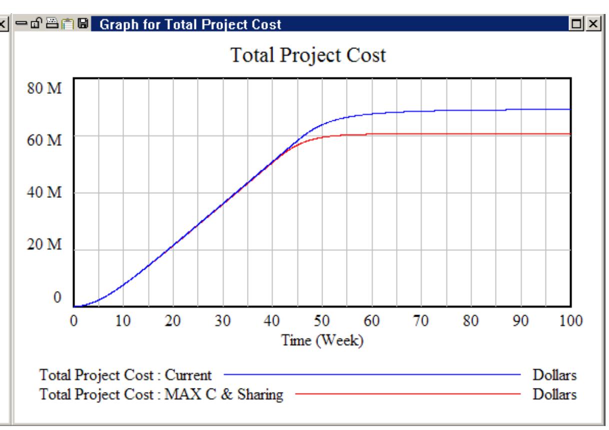


Figure 24: Total Project Cost

Conclusions

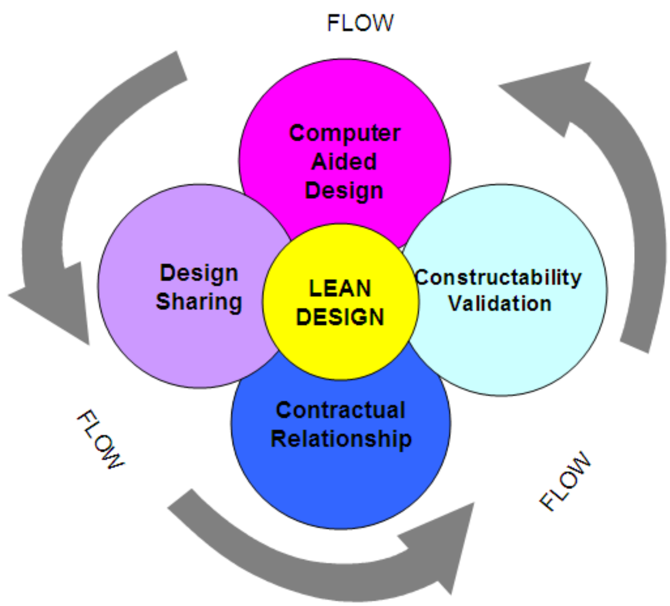
Historical resistance by the construction industry to accept ideas from manufacturing has limited the acceptance and implementation of lean construction. The traditional transformational view of construction is contrary to lean principles, which shift the focus from craft production to the overall process (including design). The goal of lean construction is to make value-added activities flow, which can only be accomplished if lean concepts are included from the very beginning of the design process.

Lean Design can be accomplished by considering constructability in the design in order to improve flow at the job site. This can only be accomplished by collaborative decision making with the A/E, owner and subcontractors. Design should be selected to enable efficient construction operations, which must be accomplished through collaboration and constructability validation. Traditional constructability concepts developed in the 1980s still apply to lean construction and can be enhanced through the consideration of how to make the process flow. Standardization of design elements, modularity, and pre-assembly are all methods that can improve flow on the construction job site.

In addition to consideration of constructability concepts, design teams must be expanded to include contractors, subcontractors, and materials suppliers. Communication among all parties will be difficult; however, advances in information technology are making it easier to communicate. Through universal access, all key players can work cooperatively on a design instead of isolated from each other. With increased cooperation and collaboration, it is not difficult to incorporate lean principles into construction practices. But, with the development of Information Technology and Building Information Modeling most obstacles are easily mitigated.

The following is a proposed conceptual framework for lean construction, as derived from a synthesis of material discussed in both the literature review and analysis sections of this study.[7] The underlying set of ideas are to promote a systemic lean approach to construction design. There are four main parts to the framework; Contractual Relationship, Collaborative Design Sharing, Constructability Validation, and Information Technology. See below for a graphic representation. The four parts of the framework are integrated together and supported by a contractual relationship. Although, ideally design and construction teams would not need a contract specifying their requirements or commitments, real work problems have proven that these relationships need to be formal to be valid.

[7] The original thesis for this study, which includes an extensive literature review, can be found at http://lean.mit.edu. A list of selected references and works cited from the literature review are found at the end of this paper.



Lean Design Framework

Contractual Relationship

Design and Construction entities on a project need to be organized in such a way that they all function as a single company with a single goal with no competition amongst them for profit or recognition. In government contracts this is especially critical; good ideas are often stifled due to design restrictions set by the government. Contractual relationships need to be established to question these restrictions and ensure design meets the government's intent with best value. Therefore, each member of the management-design-build team shares completely the responsibility for the entire project. Also, the team jointly sets about correcting deficiencies or problems wherever they pop up without regard to who caused the problem or who is going to pay for the damages. If all stakeholders share the responsibilities and the rewards, innovative design solutions will be shared, providing the government with the best value design.

Constructability Validation

The separation of the design and construction phases in projects makes it difficult to create flow in the overall process. Because the A/E industry views design as a distinct process with its own product, there is little incentive to spend time and money on constructability issues. The System Dynamics model has shown that constructability in the early stages of design will reduce the number of errors, time and money in a construction project. This constructability validation will reduce RFIs (Request For Information), which inherently reduces the time spent by both government and A/E in construction contract administration. Therefore, the framework has included the need for constructability validation from all contractors and subcontractors as one of the four factors.

Collaborative Design Sharing

Only through collaborative design sharing amongst A/E and owner (government) can design optimization be accomplished. Benefits such as standardization of design elements to be used to minimize cost and time require the collaboration of all design disciples. Design sharing can also be used as a system design validation process for the government. It is cost beneficial for Naval Base Public Works Departments to utilize standard designs on major utility systems to allow for ease of maintenance with trained personnel. Collaborative Design Sharing with the A/E and owner reduces design changes late in design or during construction by the owner, due to incompatibility with existing base systems, or A/E due to design errors.

Computer Aided Design

Two of the three case studies used for this study (not presented in this paper) demonstrated that computer aided design such as Building Information Modeling reduced the number of RFI's, cost over runs and time on a construction project. BIM promotes collaborative sharing of information and design validation. Again, these benefits from improved sharing and General Contractor-client interaction are also supported by the findings from the System Dynamics model used in this study.

In conclusion, the framework proposed in this paper for lean construction is supported by both the literature review and the analytical portion of this study. As seen, System Dynamics provides an outstanding analysis tool for better understanding the complexity of the construction design and implementation process, specifically in understanding the critical role that delays and non-linear feedback processes have on the system. Perhaps more importantly, this study suggests that System Dynamics might possibly have some potential to provide insights into a number of other military related problems, ranging from understanding the dynamic implications of strategic decisions to solving the current manpower dilemma and improving military hardware. Indeed, as the world becomes more complex and military endeavors continue to follow suit, such a tool might prove critical to protecting our National Security interests

References/Works Cited

Akao, Y. **"An Introduction to Quality Function Deployment."** Quality Function Deployment (QFD): Integrating Customer Requirements into Product Design. Akao, Y. (ed.), Productivity Press, Cambridge, Massachusetts, 1990: pp1-24.

Alarcón, L.F. **"Training Field Personnel to Identify Waste and Improvement Opportunities."** Lean Construction. Alarcón, L.F. (ed.), A.A. Balkema, Rotterdam, The Netherlands. 1997: pp 391-401.

Ashley, David B, Lurie, Clive S. & Jaselskis, Edward J. **" Determinants of Construction Project Success."** Project Management Journal, Vol. XVIII, No. 2, 1987: pp. 69 - 79.

Austin, S., Baldwin, A., and Newton, A. **"Manipulating the Flow of Design Information to Improve the Programming of Building Design".** Construction Management and Economics, London. 1994: pp 445-455.

Ballard Glenn. "**The Last Planner System of Production Control.**" Proc. Seventh Annual conference of the International Group for Lean Construction (IGLC-7), Berkeley, 1999.

Ballard, Glenn. **"The Last Planner System of Production Control."** University of Birmingham Doctoral Thesis 2000.

Ballard, Glenn . **"Can Pull Techniques Be Used IN Design?"** Proceedings of the Conference on Concurrent Engineering in construction, Espoo, Finland, August 1999 pp 6-14.

Ballard, G. **"Improving Work Flow Reliability."** Proc. Seventh Annual Conference of International Group for Lean Construction (IGLC-7), Berkeley 1999.

Ballard, Glenn and Koskela, Lauri. **"On the Agenda for Design Management Research."** Proceedings of the 6th Annual Conference of the International Group for Lean Construction, Guaruja Beach, Brazil, August, 1998.

Ballard, G and Koskela, L. **"On the Agenda of Design Management Research".** Proc. Sixth Annual Conference of the International Group for Lean Construction (IGLC-6) Guruja, Sao Paulo, 1998.

Brown, Kevin. **"Re-Architecting the DoD Acquisition Process: A Transition to the Information Age."** MIT Master's Thesis, February 2006.

Burati et al., "**Causes of quality deviation in design and construction."** ASCE Journal of Construction Engineering and Management, 1992: pp 34-49.

Burati, James L., Mathews, Michael F. & Kalidindi, S.N. "**Quality Management in Construction Industry**." Journal of construction Engineering and Management, Vol 117, No.2, 1991:pp 341-359.

Checkland, P.B. **Systems Thinking, Systems Practice.** John Wiley & Sons, Chichester. 1981.

Clark, Kim B. & Fujimoto, T. **Product Development Performance**, Cambridge, MA: Harvard Business Press,1991.

Cnuddle, M. "**Lack of Quality in Construction – Economic Losses**." European Symposium on Management, Proceedings, 1991: pp. 508-515.

Dasu, Sriram and Eastman, Charles**. Management of Design: Engineering and Management Perspectives.** Kluwer Academic Publishers, Boston, MA: 1994.

Dupagene, A. "**Computer Integrated Building. Strategic Final Report**.", ESPRIT II: Exploratory Action No 5604. December 1991: p24-28.

Edgar, Alan, "**Right Thinking About BIM and The National BIM Standards Committee**",2006: http://www.aecbytes.com/buildingthefuture/2006/BIMstandards.html

Fabricio, M., Melhado, S and Baia, J. **"Brief Reflection on Improvement of Design Process Efficiency in Brazilian Building Projects."** Proc. Seventh Annual Conference of the International Group for Lean Construction (IGLC-7), Berkeley, 1999

Finger, S., Gardner, E., & Subrahmanian, E. **"Design support systems for concurrent engineering: A case study in large power transformer design."** Proceedings of the International Conference on Engineering Design, ICED 1993: The Hauge.

Green, Steven. "**The technocratic totalitarianism of construction process improvement: a critical perspective."** Engineering, Construction and Architectural Management, 1998: pp 376-388.

Hendrickson, Chris. **Project Management for Construction**. Pittsburg: PA Prentice Hall, 2005.

Jensen R.W. and Tonies C.C. **Software Engineering**, Prentice Hall, Englewood Cliffs, NJ, 1979.

Kirkwood, Craig W. "**System Dynamics: A Quick Introduction"**,1998:Oct 12. http://www.public.asu.edu/~kirkwood/sysdyn/SDIntro/SDIntro.htm

Koskela, L. & Huvolia, P (1997). **"On Foundations of Concurrent Engineering"** in Anumba,C. and Evbuomwan, N (eds). Concurrent Engineering in Construction CEC91. London 3-4 July.

Koskela, L. **"Management of Production in Construction; a Theoretical View."** Proc. Seventh Annual Conference of the International Group for Lean Construction (IGLC-7), Berkeley, 1999.

Levitt, R.E., Cohen, G.P., Kunz, J.C., Nass, C.I., Christiansen, T., and Jin, Y. **“The ‘Virtual Design Team’: Simulating How Organization Structure and Information Processing Tools Affect Team Performance.”** in Carley, K.M. and Prietula, M.J. (eds.), Computational Organization Theory.LawrenceErlbaum Assoc. Pubs., Hillsdale, N.J. 1999.

Liker, Jeffrey K., Fleischer, Mitchell, and Arnsdorf, David .**“Fulfilling the Promises of CAD.”** Sloan Management Review, Spring 1992: 74-86.

Matthews, Owen and Howell, Gregory, “**Integrated Project Delivery An Example of Relational Contracting**.” Lean Construction Journal 2005, p 46-61.

Minami, Nathan. **“Re-Architecting the Battalion Tactical Operations Center: Transitioning to Network Centric Operations.”** MIT Master’s Thesis, February 2007.

Pixlery, David. “**Applying Lean Principles to Healthcare Construction.”** LCI Symposium 2006 pp-10-11.

Plossl, George W. **Managing in the New World of Manufacturing**. Englewood Cliffs. Prentice Hall, 1991.

Rodrigues, Alexandre and Bowers, John . “**The role of system dynamics in project management.”** International Journal of Project Management, Vol. 14, No. 4, 1996: pp. 213-220.

Rojas, E. M. and Songer, A.D. **“Web-centric systems: a new paradigm for collaborative engineering.”** Journal of Management in Engineering. Vol. 15, No. 1. 1999: pp. 39-45.

Seymour, D. and Rooke, J.**“The culture of industry and the culture of research.”** Construction Management and Economics, 13(4),1995: pp 511-523.

Shillito, Larry M.,DeMarle David J. **Value: Its Measurement, Design and Management .** New York: Jonh Wiley & Sons, Inc., 1992

Shingo Shigeo. **Non-stock production**. Cambridge, MA:Productivity Press, 1988.

Songer, A.D., Diekmann, J., Hendrickson,W., and Flushing, D.**“Situational Reengineering: Case Study Analysis.”** Journal of Construction Engineering and Management, ASCE, Vol. 126, No. 3. 2000: 185-190.

Sterman, John D. **“Business Dynamics: Systems Thinking and Modeling for a Complex World.”** The McGraw-Hill Companies, Inc. Boston, MA. 2000.

Sterman,J.D. “**Systems Dynamic Modeling for Project Management**.” Working Paper, Systems Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA 1992: pp1-6.

Tzortzopoulous, P., and Formoso, C.T. **“Considerations on Application of Lean Construction Principles to Design Management”**, Proc. Seventh Annual Conference of the International Group for Lean Construction (IGLC-7), Berkeley, 1999.

Ward, Allen, Jeffrey K. Liker, John J. Cristiano, and Durward K. Sobek II. **“The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster.”** Sloan Management Review, Spring 1995: pp. 43-61.

Warszawski, A. **Industrialization and Robotics in Building: A Managerial Approach**. New York :Harper & Row,1991.

Womack, James P., Daniel T.Jones and Daniel Roos, **The Machine That Changed the World: The Story of Lean Production**, New York: Rawson and Associates:1990.

Womack, James P., Jones Daniel T., **Lean Thinking**, New York: Free Press:2003.