Causes and Effects of Rework on the Delivery of Healthcare Facilities in California

by

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Abstract

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This research focuses on identifying the causes of rework within a design and permitting process of healthcare facilities in California. Causes of rework were identified and categorized. Three computer simulations were created to illustrate the effect of rework on system performance. One explores the throttles affecting a production process. The other two illustrate the effect of rework on two organizational case studies.

Research extending a taxonomy describes causes of rework in the process. I obtained data from industry workshops to determine the current state process for the healthcare construction industry. I used a multi-tier categorization framework to classify the causes of rework. This laid the foundation for further exploration through computer simulation.

The first case study, workflow of a mechanical contractor, illustrated the complexity involved in the process from their point of view. I used computer simulation to reveal the pressures on the construction process due to incomplete drawings and changes to them. I determined that implementing a delayed management strategy is one way to reduce negative rework.

Understanding demand and capacity using simulation models provides intuition on the elements affecting workflow variation in a production process. I identified three throttles that control production throughput: (1) inflow of projects, (2) resource capacity, and (3) likelihood of rework. Simulations highlight the tradeoffs management can make between the latter two.

The second case study, effect of alternative review on workflow, describes both the current and future state process of a plan review agency. I obtained data from them and constructed a model to simulate their workflow. Simulations showed that an alternative review process can improve system performance.

This research showed that negative rework can be detrimental to system performance. To improve performance we must break free from traditional project roles, where information is isolated and protected, and move to an environment where we understand the workflow of others and of all combined. The occurrence of negative rework can be reduced by engaging more stakeholders, earlier in design, fostering an integrated and collaborative environment.

## ACKNOWLEDGMENTS

First and foremost, I want to thank my family for supporting me through this academic journey. To my wife, Maricar, you are the bedrock in our family and the driving force behind my accomplishments. You kept me focused on the end goal and always put things in perspective when I was down; you were a critical piece in finishing this dissertation. To my son Nolan, you are my inspiration in life. My love for you grows everyday and you continue to make me a better person. The both of you helped me through all of those late nights and early mornings as I prepared for my classes, my exams and the writing of this dissertation. Second, I would like to thank Professor Tommelein for all of her insight. You pushed me to explore the theoretical underpinnings of my research and I know this product would not be nearly as good without your help. Third, I would like to thank Professors Ballard and Rundall for their valuable input. Fourth, I would like to thank my 407 colleagues that provided technical support in developing the research presented in this dissertation. Finally, I would like to thank my industry partners for answering all of my questions. Without those mentioned above, I would not have finished this dissertation, and for that, I am forever grateful.

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# 1. INTRODUCTION

## 1.1 Motivation

I am a commissioned officer in the United States Air Force and have served our country for over 12 years. This research effort is grounded in the experiences that I have had in the military. Specifically, after the events of September 11, 2001, I was deployed to the United Arab Emirates, to an airbase to construct an 1,140' by 780' aircraft parking ramp that would support the air campaign in Operation Enduring Freedom to drive the Taliban from power in Afghanistan. As the officer in charge, I was responsible for the entire design, construction, and procurement of the $26M project. This aircraft parking ramp had to be ready for operation in less than six months to include taxiways, apron, airfield lighting, a fire station, two warehouses, and all supporting utilities like water, sewer, electricity, and HVAC.

Due to the time constraint, the team of 300 personnel I was responsible for was extremely motivated to support the mission of the United States. I was deployed to location two months earlier to start the design and was involved with soil borings to determine the foundation requirements. The entire site would have to be elevated over six feet with various amounts of soil. Also, design standards were developed to mitigate the harsh soil conditions. I was able to complete the design in less than two months.

In the back of my mind, I kept thinking about how to prevent rework on this project because time was ticking and we did not have the time to spare. One way to ensure that the design drawings would be completed without large errors was to include various design professionals and tradesmen in my design team. The design engineers included a mechanical and electrical engineer. However, some of the most valuable members were the craftsmen, including a pavement engineer familiar with asphalt and concrete, an airfield lighting expert, a utility specialist, a structural specialist, and a contracting specialist.

Building in a foreign country posed a difficulty none of my personnel had faced before. Our goal was to build a ramp and supporting infrastructure to the highest quality possible. In order to build a project that would stand the test of time, we consulted local industry members; fortunately, Bechtel was more than willing to help in this situation. They alerted us to significant errors they had made in the past when constructing large concrete projects in the Middle East and they pointed out the importance of tending to two issues. The first issue was the use of British standards for concrete design and testing, something that would require us to develop an understanding of block testing (versus cylinder testing as specified by the American Concrete Institute (ACI)). The second issue was aggregate. In the Middle East, much of the aggregate is river rock: smooth and rounded. By contrast, American engineers learn to use aggregate with fractured faces to ensure interlocking forces occur. Also, in the Middle East, aggregate is not washed for fines because the sheer amount of dust in the area would make such an action futile. In other words, we would have to abandon ACI standards and work with the local engineers to understand the implications of these issues, using higher moisture content in the concrete mix and hot weather concreting procedures. It was this upfront acceptance of working in a foreign situation that aided us greatly. We did not come into the situation requiring the job be completed to ACI specifications.

An additional difficulty of building in a foreign country is overcoming language and cultural barriers. Furthermore, we had to obtain approval of the design drawings through both the local and the military building departments. We engaged their departments very early and explained that we were building to a specific set of airfield standards. In other words, we involved local industry as much as possible to get their expert help. This greatly reduced the number of errors that might have otherwise occurred. In retrospect, our decision to involve local experts early on was likely the most important reason the project moved so smoothly without needing rework.

During the construction phase, specifically during concrete placement, we operated 24 hours a day. There was no room for rework. To prevent rework, we met extensively during the day and night to ensure concrete quality was up to standard, and we constantly poured and tested cubes throughout the project. In the field we developed built-in quality procedures for dowel placement which helped considerably during the 30,000 dowel installation.

This project was extremely successful, requiring minimal amounts of rework. This kept the team’s motivation very high throughout the project and I believe the synergies created allowed this project to succeed.

When I entered the military, my goal was to obtain my PhD and become a professor like my father. His love for teaching lasted over 26 years. As a result, I competed and successfully won the opportunity to obtain my PhD through the US Air Force. The US Air Force will draw down its work force over the next few years and is using lean concepts to improve process efficiencies. I knew I wanted to study lean concepts for my PhD. Therefore, with the concept of understanding rework and its impact, and the ability to apply lean concepts to mitigate rework effects became the focus of my research.

I also wanted to focus my research on a government agency because I work for a large government agency. Government agencies are similar in many ways and what I learn from one agency, can be applied to another agency. These similarities include: not being able to hire and fire people because all procurement must be competitively bid out, and being required to deal with the lowest common denominator so as not to exclude a population. Avoiding the embedding of errors can have an enormous impact on design, permitting, and construction schedules. Studying how this can be done systematically is the subject of this dissertation research.

I decided to focus on the permitting process for construction of California healthcare facilities because of the government agency tie and the opportunity I had to gain access to research data. In addition, my professors, Dr. Glenn Ballard and Dr. Iris Tommelein, with members of the Project Production Systems Laboratory have reached out to the healthcare facility industry in California to help improve production processes. One process that needs improvement is the permitting process which involves owners, designers, contractors, and regulators.

### 1.1.1 Escalating Costs for California Healthcare Facilities

The cost of constructing healthcare facilities is escalating in the state of California: for example, in northern California, it has risen from \$330/GSF to around \$620/GSF from 2003 to 2007 (figure 1-1), an increase of 88% in four years. This cost increase is linked to the seismic requirements imposed by the Healthcare facility Safety Seismic Act of 1973, the cost of land, and escalation of construction costs.

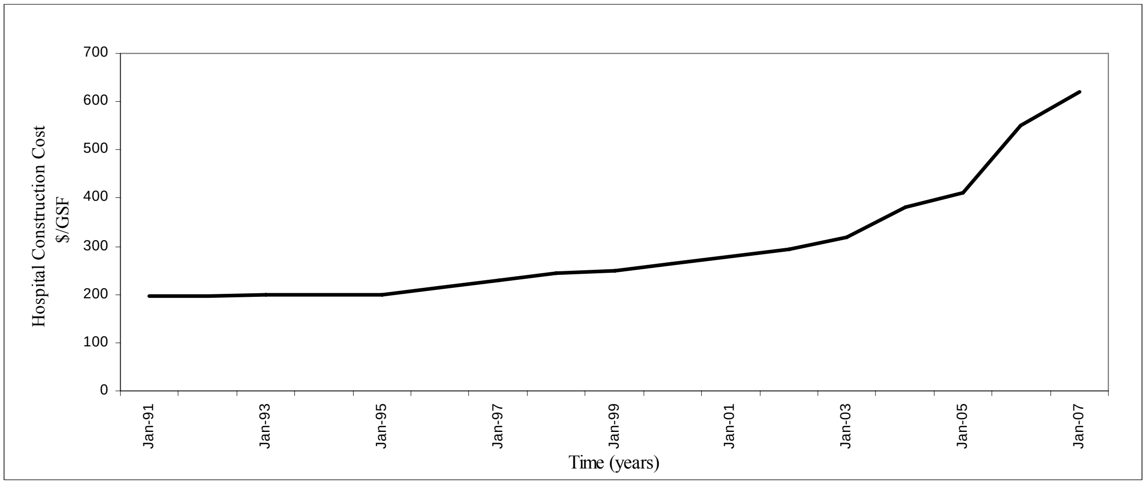



Figure 1-1 Cost Escalation of Construction in Northern California (modified from Morris 2007)

This rise in cost for California healthcare facilities is more pronounced than it is for non-California healthcare facilities (figure 1-2).

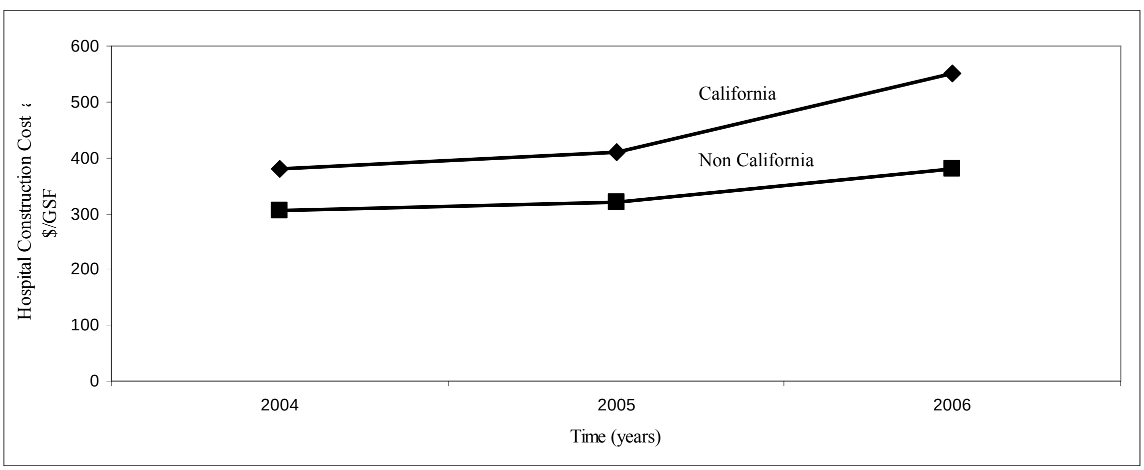



Figure 1-2 California vs. Non-California Cost of Construction (modified from Morris 2007)

The high demand for construction services in California is one major contributor to the cost escalation. Figure 1-3 reflects this demand by showing an increase in employment of construction personnel in California for every year since 1997, except between 2002 and 2003. Even during the dot com crash of 2001, construction employment continued to increase for about another year.

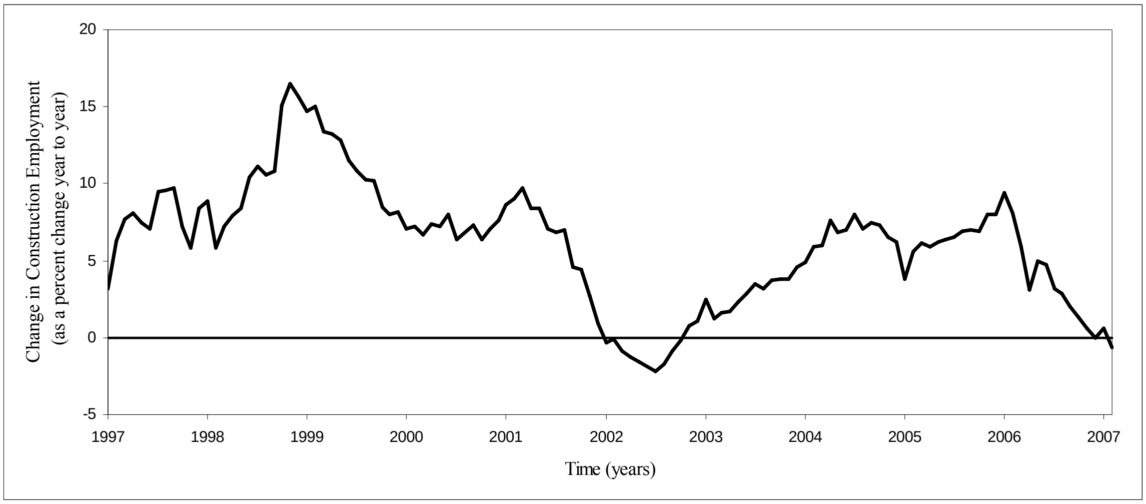



Figure 1-3 Construction Employment in California (Bureau of Labor Statistics 2007)

A reduction of available contractors to work on healthcare facility projects occurs due to several reasons including: (1) healthcare facility construction is a complex process and requires experienced, specialized contractors, (2) the qualification and experience requirements, with respect to bonding and insurance, created a large barrier to entry for new contractors, and (3) industry member perception of the extensive regulatory, review, and inspection required by the state of California limits the number of contractors willing to take on healthcare facility construction. Therefore, due to small numbers, it is possible to affect change in the permitting process by engaging those involved to develop a new process that can reduce, if not totally eliminate rework. Additional information on the issue surrounding California healthcare facility construction is located in section 2.6. Rework means different things to different people. The following section defines rework in the context of this dissertation.

### 1.1.2 Rework Definitions

Some practitioners speculate that a major contributing factor to the rising cost of healthcare facility construction is the rework that occurs in the upfront planning, design, and permitting phases. What rework are they referring to? Following are four definitions of rework:

1. Total direct cost of redoing work in the field regardless of initiating cause (Construction Owners Association of Alberta 2001).
2. Activities in the field that have to be done more than once or activities that remove work previously installed as part of the project (Rogge et al. 2001).
3. The unnecessary effort of redoing a process or activity that was incorrectly implemented the first time (Love et al. 2000).
4. Negative iterations of work that can be eliminated without loss of value or without causing failure to complete the project (Ballard 1999). Ballard classifies rework as either positive or negative. Positive rework adds value; for example, it occurs when designs are reworked and participants in the design process leave with a better understanding of customer requirements. Negative rework does not add value; for example, it occurs when duct work is initially installed and then has to be removed because interior walls were moved to accommodate a design change. Negative rework extends projects schedules.

The definition by Ballard is used in this research.As the facility delivery process from conception to construction completion is extended, the total cost increases. One way to control such costs is to reduce the upfront planning, design, and permitting phase, which in California can take on the order of two to five years for a new healthcare facility. This upfront process involves many different organizations to include the owners, architects, engineers, and in California, the Office of Statewide Health Planning and Development (OSHPD), and the Department of Health Services (DHS). The role of OSHPD and DHS is described in section 2.6.

The iterative process of the upfront design and permitting process can be both positive and negative in nature. However, increased design iterations may create delays leading to cost escalation and add time to project schedules. Iterations may be due to owner changes, changing regulations, and the handoffs between the different organizations as mentioned. The information required to design a healthcare facility flows in large batches or chunks of work that, when taken together, add to the delays. Introduce an error in the design and the delays exacerbate. Rising cost and schedule growth of projects is directly correlated with rework, due to the added effort it takes to resolve and mitigate the rework (Love 2002).

## 1.2 Problem Statement

Healthcare facilities are complex systems requiring significant effort in planning, permitting, and construction. Due to (1) intricate designs, (2) stringent seismic (upgrade) requirements in California, (3) cost escalation, (4) labor shortages, and (5) compressed schedules, cost and schedule overruns are prevalent and customer value is reduced.

Construction costs in California have escalated at a rate between 8 - 12% per year and are projected to further increase in 2009 and 2010 (CHA 2008). Therefore, it is reasonable to assume a 1% per month cost escalation for California healthcare facility construction. Previous studies have found the cost of rework in design and construction to range from 2% to 12% of the contract cost (Burati et al. 1992, Josephson and Hammarlund 1999, Love et al. 2000). For example, it costs approximately $2M per bed to construct a new healthcare facility, therefore, a 50-bed healthcare facility costs on the order of $100M. Using a cost escalation of 1% per month equates to $1M per month of delay. Informal surveys of design teams have revealed estimates as high as 50% of design time spent on needless (negative) iteration (rework) (Ballard 1999). Reducing the time to design and permit a healthcare facility in California can reduce the overall time to deliver a healthcare facility which improves business plans.

## 1.3 Research Objectives

This research has six objectives.

1. Develop a taxonomy of rework as it applies to the California healthcare facility industry, building on existing literature where possible.
2. Develop a computational model to understand how a management strategy affects field construction variation while operating in a continually changing design environment.
3. Develop a computational model to understand demand and capacity and the influence that rework has on a simple production model.
4. Explore throttles on a production model and how they might relate to a state permitting agency.
5. Develop a computational model of a California facility permitting agency to understand how an alternative review process affects organizational workflow.
6. Reveal process inefficiencies by studying an existing design review process.

## 1.4 Research Questions

This research poses eight questions.

1. What are the root causes of rework in the healthcare facility construction industry?
2. What strategy should a mechanical contractor adopt to avoid negative rework during the construction phase?
3. What are the throttles on a simple design review process and how are they controlled?
4. What is revealed from a sensitivity analysis conducted on a plan review simulation?
5. How can a plan review system be stabilized for mean time to permit and improve predictability?
6. How can errors in healthcare facility design be detected and corrected?
7. What is the effect on the plan review agency if benefits from an alternative review process are not realized?
8. What strategy should a plan review agency adopt to avoid negative rework during the design and permitting phase?

## 1.5 Hypothesis

This research poses two hypotheses.

1. Reducing rework in the planning, designing, and permitting phases reduces the lead time to deliver healthcare facilities.
2. Implementing an alternative review process reduces embedded design errors and reduces the time to permit healthcare facility designs.

## 1.6 Methodology

This research uses qualitative and quantitative techniques to understand the impact of rework on the delivery of healthcare facilities in California. Qualitatively, I used purposeful sampling to obtain the data samples. I used cause and effect diagrams to expand an existing taxonomy of rework. Also, I used in depth interviews to develop a reflective survey for design and construction personnel and to validate the two computer models presented in chapters 4 and 5. Quantitatively, I used computer simulation, specifically discrete event simulation to research two types of organizational workflow and lean production theory to demonstrate the impact rwork can have on process efficiency. I analyzed the database in conjunction with resampling techniques to obtain sample statistics used in the discrete event simulation presented in chapter 6.

### 1.6.1 Qualitative Research

Five types of qualitative research exist: (1) narrative-biography, (2) phenomenology, (3) ethnography, (4) grounded theory, and (5) case studies (Creswell 2007).

1. A Narrative-biography consists of interviewing a few individuals where data is collected through their stories and experiences, and then chronologically ordering them. Narrative-biographical research has its roots in literature, history, anthropology, sociology, sociolinguistics, and education (Chase 2005). The challenge of this type of research is accounting/correcting for the biases involved. The researcher must understand the context of the individual's life, for example, what is their personal and political background (Creswell 2007). Issues dealing with collecting, analyzing, and reporting the individual stories must also be addressed, such as: Who owns the story?

Who can tell it? Who can change it? Whose version is convincing? What happens when narratives compete? As a community, what do stories do among us? These questions must be addressed prior to completing a successful narrative-biographical study (Pinnegar and Daynes 2006).

2. Phenomenology research differs slightly from a narrative-biographical study in that it describes a concept or phenomenon through multiple subjects through their life experiences. This research attempts to describe what all of the participants have in common, for example, how people experience grief, anger, or insomnia (Creswell 2007). The purpose is to reduce life experiences from a phenomenon into a universally understood situation. This type of research ultimately describes what people experience and how they experience it (Moustakas 1994). Phenomenological studies are primarily used in sociology, psychology, nursing and education (Borgatta and Borgatta 1992, Giorgi 1985, Oiler 1986, Tesch 1988). The challenges are that the researcher must have a broad understanding of the assumptions; the participants must be carefully selected so that they have experienced the phenomena so a common understanding can be achieved, and finally it can be difficult to put boundaries on the personal experiences obtained in the study (Creswell 2007).
3. An ethnography focuses on a cultural group to examine shared patterns. These groups, for example, can be teachers in an entire city or construction workers who are involved with healthcare facilities, which are studied over time to understand their interactions. Behaviors, beliefs, and languages are examples of potentially shared patterns within a cultural group. An ethnography uses participant observation to collect data where the researcher is involved with the day-to-day lives of the people

and records observations and interviews with the cultural group. The challenge with ethnographies is the extensive time required to complete them, with much of that time occurring in the field. The researcher must maintain objectivity but many times becomes extremely biased in the information that is presented in an ethnographic study (Creswell 2007).

4. Grounded theory research attempts to go beyond describing a common experience that a phenomenological study provides and tries to generate or discover a theory, an abstract analytical scheme of a process, action, or interaction through the views of a large number of participants. The key difference is that the theory is not just developed, but it is grounded in data from participants who have experienced the process (Strauss and Corbin 1998). This research method is also used in sociology, nursing, education, and psychology. The challenges with grounded theory research are that theoretical ideas must be set aside so the proposed theory can evolve. The research is difficult to conduct because it is difficult to know whether or not enough and sufficiently detailed information about the theory has been obtained. One technique that can be used to determine if data is sufficient is to collect another sample that is completely independent from the original sample (Creswell 2007).

5. Case studies are a common research method in psychology, sociology, political science, social work (Gilgun 1994), business (Ghauri and Gronhaug 2002), and city and regional planning (Legates and Stout 2007). Case studies are a useful research method to conduct experiments in order to understand how and why a phenomenon occurs, where behavioral events are not controlled and the event is occurring in real time. Case studies try to understand complex social phenomena that can not be

studied or replicated in a laboratory setting. The case study allows the meaningful characteristics of real life events, such as organizational, leadership, and managerial decisions and processes to be retained and evaluated in a systematic way (Yin 2002). Case studies are the focus of this dissertation.

This dissertation will focus its data collection on documents, interviews, direct observation, and participant observation. Table 1-1 shows the strengths and weaknesses of each of these data sources.

| Source of data | Strengths | Weaknesses |
|---|---|---|
| Documentation | • Stable - can be reviewed repeatedly<br>• Unobtrusive - not created as a result of the case study<br>• Exact - contains exact names, references, and details of an event<br>• Broad coverage - long span of tie, many events, and many settings | • Retrievability - can be low<br>• Biased selectivity, if collection is incomplete<br>• Reporting bias - reflects (unknown) bias of author<br>• Access - may be deliberately blocked |
| Archival records | • (Same as above for documentation)<br>• Precise and quantitative | • (Same as above for documentation)<br>• Accessibility due to privacy reasons |
| Interviews | • Targeted - focuses directly on case study topic<br>• Insightful - provides perceived causal inferences | • Bias due to poorly constructed questions<br>• Response bias<br>• Inaccurate due to poor recall<br>• Reflexivity - interviewee gives what interviewers want to hear |
| Direct observation | • Reality - covers events in real time<br>• Contextual - covers context of event | • Time consuming<br>• Selectivity - unless broad coverage<br>• Reflexivity - event may proceed differently because it is being observed<br>• Cost - hours needed by human observers |
| Participant observation | • (Same as above for direct observations)<br>• Insightful into interpersonal behavior and motives | • (Same as above for direct observations)<br>• Bias due to investigator's manipulation of events |
| Physical artifacts | • Insightful into cultural features<br>• Insightful into technical operations | • Selectivity<br>• Availability |

Table 1-1 Six Sources of Data: Strengths and Weaknesses (Yin 2002)

Case study documentation is used to corroborate and augment data from other sources. Documentation can come in the forms of letters, agendas, announcements, meeting minutes, proposals, progress reports, formal studies, newspaper articles, and internet websites. Documents clarify names and titles within organizations. They can also provide specific verification of other data sources and inferences can be made from them. For example, understanding how documents are distributed throughout an organization can provide information on how formal and informal communication works. However, one must be careful in developing theory based on such inferences because they can easily be wrong. This type of data will be used in this dissertation.

Archival records encompass service records, organizational records, maps, charts, lists, survey data, and personal records. The strengths and weaknesses are similar to documentation yet differ in that privacy issues may prohibit access. These types of records are produced with an audience in mind and that must be considered in understanding their bias, usefulness, and accuracy. This type of data will not be used in this dissertation.

Interviews will be a source of validation for the case study research. Interviews differ from surveys in that the question and conversation is allowed to flow through different topics as long as the main points of questioning are addressed. An interview may provide the researcher with information they did not intend to collect (Rubin and Rubin 2005). Questions posed in a semi-structured manner produce data with less bias. For example, asking "why" a particular process has occurred may put the interviewee on the defensive, while asking "how" a process occurs retrieves more accurate information (Becker 1998). Four types exist: (1) open ended, (2) semi-structured, (3) structured, and (4) focused. Open ended interviews consist of questions that leave the answer entirely up to the respondent. Semi-structured as mentioned above allows for more of a conversation to occur between the participant and the researcher. Structured interviews have a set of questions and the interview does not deviate from that set of questions. Focused interviews are typically set up to occur within a certain time frame, an hour for example. This dissertation used semi-structured interviews.

Direct observation can range from formal to casual. Formal observation occurs through a defined protocol that allows the field worker to measure for example the number of times a certain behavior occurs during the observational period (Yin 2002). Casual observation does not require a specific protocol of what needs to be observed. The researcher is generally observing a situation and recording data that is important to him/her. This dissertation will not use direct observation.

Participant observation is a special mode of observation in which the researcher is directly involved with the action that is being observed. This type of observation occurs in many city and regional planning studies. For example, in The Urban Villagers, Gans (1962) studied the life of Italian Americans as a participant observer. The data was collected from a neighborhood in which he was a long time resident. A major strength of participant observation is that it allows the researcher to gain access to areas people conducting direct observations may not have access to. In addition, it provides the ability of the researcher to perceive reality from someone who is "inside" the case study. However, this type of data can be biased and the participant observer may become a supporter of the group or organization being studied (Yin 2002). This dissertation will not use participant observation.

Physical artifacts may be collected during site visits and may allow the researcher to understand current policy and procedures that govern an organization (Yin 2002).

Project schedules, change orders, and faxes are examples of physical artifacts. This dissertation will not collect physical artifacts.

### 1.6.2 Quantitative Research

The quantitative research techniques used in this work centers on discrete event simulation and database analysis. System models are divided into two categories: (1) deterministic and (2) stochastic (figure 1-4). Deterministic system models have no random components. For example, when modeling a chair lift servicing a ski resort, assuming that the chair lift machinery never fails and the queue is always full, a constant-velocity model can be developed that will determine how many people reach the top in a certain time frame. However, at some level a system model involves randomness. A stochastic model brings random behavior into the picture, for example, engines fail, people fall off the chair lift, and people show up at the lift at random times.

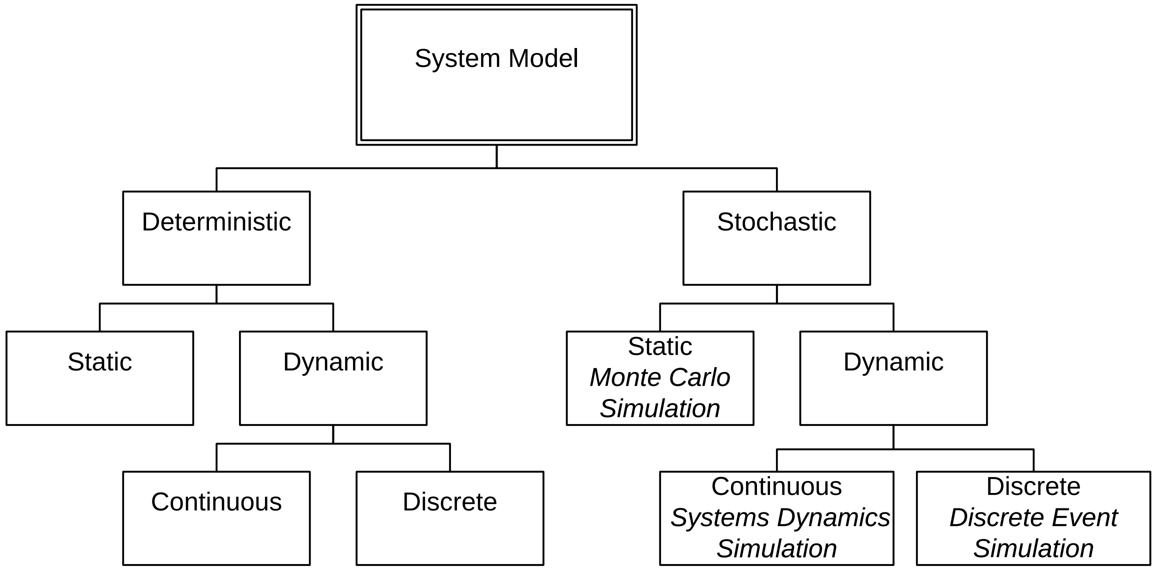



Figure 1-4 System Model Taxonomy (Leemis 2006)

The advantage of a discrete event simulation is it can accommodate randomness and be used when other mathematical characterization is too complex to give a closed-form solution.

Stochastic system models are either static or dynamic. A static system model is one where time is not a concern. A well known static stochastic model is a Monte Carlo simulation which uses a random number generator (Law 2007).For example, if the question is “Five million people shop at a chain retail outlet, what is the probability that each one spends over $1,000 dollars?” the simulation program developed to answer this question should be a static model because it doesn’t matter when during that week the shoppers made their purchases. However, if the question is “What is the probability that a shopper will spend over $1,000 dollars as the weeks approach Christmas?” then the simulation program should be a dynamic model. This occurs because shoppers are more inclined to spend money as the holiday season arrives. A dynamic model should be considered where time is important to the system (Leemis and Park 2006).

A dynamic stochastic model can be continuous or discrete. Continuous dynamic models are best represented by classical mechanical systems that have continuously evolving variables and by systems dynamics models (e.g., Sterman 2002). An accelerating vehicle, a skier moving downhill, or a block sliding down are examples of models where continuous movement is described by differential equations that model continuous changes over time. Systems that perform piecewise functions, as in transforming raw metal into a HVAC duct or conducting a review of healthcare facility drawings, are best described using a discrete event simulation model. These models are stochastic because they can experience randomness in the variables. They are dynamic because the evolution of time is important in understanding the system. Finally, they are 'discrete event' because significant changes in the variables are associated with events that each occur at a specific time during the operation (Leemis and Park 2006).

Discrete event simulation models can also be used to model project schedules. These models implement a network form to communicate complex concepts. Project planning using the Critical Path Method (CPM) and the Project Evaluation and Review Technique (PERT) are examples of network models that convey complex situations.

Discrete event simulations may use an activity on node representation with use nodes (Activities and Queues) connected to each other through arcs or links to describe the network(e.g., STROBOSCOPE CPM, Martinez 1996). Following is a brief description of a few simulation models.

The General Simulation Program (GSP) (Tocher and Owen 1960) introduced the concept of bound and conditional activities. An activity is considered bounded when it can start as soon as the predecessor event finishes. For example, figure 1-5 illustrates a discrete event simulation model where the activity is bounded, when a pallet is fully loaded then it can be packaged for shipment. This illustration uses the EZStrobe graphical interface (Martinez 1996). The “1” represents the number of units that will pass to Package Pallet when Load Pallet is complete.

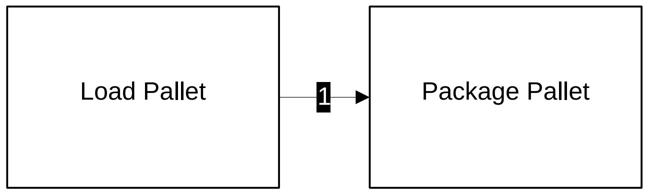



Figure 1-5 Bounded Activity

Conditional activities require at least two conditions to be met prior to the execution of the activity. For example, figure 1-6 illustrates workers and bricks both being needed for the activity of stacking to occur. The “>0, 1” located on each of the links from the workers and bricks queues controls the flow of resources. If one or more resources exist in the queue, then 1 resource is allowed to flow into the stack bricks activity.

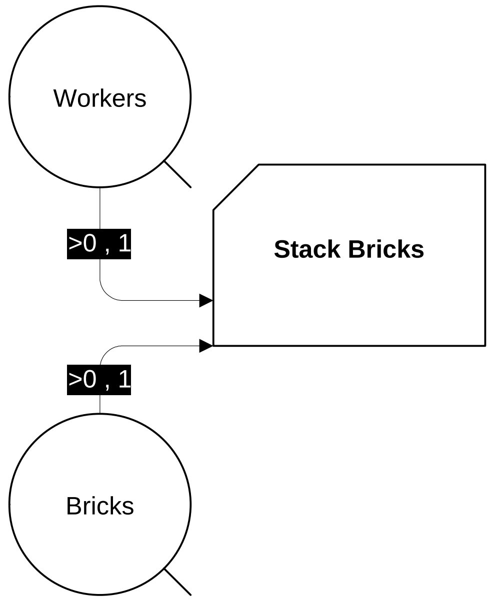



Figure 1-6 Conditional Activity

The Cyclic Operations Network (CYCLONE) was developed to model construction processes (Halpin and Woodhead 1976). CYCLONE is a simple computer model that is network based. Many other construction process models were built upon the CYCLONE model. Improvements to CYCLONE were developed by Ioannou (1989) with UM-CYCLONE and Halpin (1990) with Micro-CYCLONE. Three limitations are noted with the CYCLONE simulation engine: (1) unable to distinguish resource differences, (2) unable to determine the state of the process, and (3) unable to use resource properties dynamically to change model behavior (Martinez 1996).

The COOPS construction simulation system (Liu 1991) uses a graphical interface to allow users to draw activities, queues, and links on a computer screen. These network models allow users to create specific resources and implement statistical information on how the resources are used.

The CIPROS construction simulation system offers object hierarchies to link the simulation model to a CPM based project schedule (Tommelein et al. 1994).

The STROBOSCOPE (Martinez 1996) simulation engine, is made up of activities or processing steps (called 'Combis' = rectangles with cut-offs in the top-left corner, or 'Normals' = rectangles), holding places for resources while they are not in use and thus accumulate (Queues), symbols to model flow (arrows), and stochastic, or deterministic branching (Forks). Microsoft Visio integrates the STROBOSCOPE elements into a graphical interface as a macro and allows construction of a variety of processes. STROBOSCOPE (1) allows the state of the simulation to control the sequence of tasks and their relative priorities, (2) models resource selection schemes so that they resemble the way resources are selected for tasks in actual operations, and (3) models probabilistic material utilization, consumption, and production.

I have selected STROBOSCOPE as the programming language for this dissertation because the software is free to academic users, and it is used by various other construction researchers, among whom these terms are known. This makes it easier for models to be replicated, evaluated, and experimented with by academic and industry peers. STROBOSCOPE has been used to model 'lean' applications such as 'pull' in pipe-spool supply and installation (Tommelein 1998) and the airplane game (Rybkowski et al. 2008), multi-tasking and batching in the delivery of pipe supports (Arbulu et al. 2002), product standardization (Alves and Tommelein 2006), feedback in planning, fabrication, shipping, and installation of duct work (Alves and Tommelein 2006), and various lean production management principles applied to high-rise apartment construction (Sacks et al. 2007).

### 1.6.3 Sampling

Data sampling is discussed in this section. This dissertation sampled data in three ways. The first way I collected data was qualitatively by compiling information from a series of industry workshops. This data lists the waste or inefficient items within an existing process.

The second way I collected data was through interviews with employees of a mechanical contractor. From these interviews, I constructed a discrete event simulation model. The interview information consisted of how work flowed through their detailing, fabrication, and installation phases. I then developed a process map from this information and simplified it into a computer model. I did not calibrate the computer model because the organization did not record the amount of rework that occurred within their organization. However, the model still provides insight on the impact rework that occurs at different stages has on a process.

The third way I collected data was through both qualitative and quantitative methods. I conducted in-depth interviews with members involved with healthcare facility construction in California to understand how the facilities are permitted. I analyzed this data to construct a discrete event simulation model. I calibrated the model to existing data and then made a change to the process to understand how the changes can impact the time to permit a healthcare facility.

### 1.6.4 Qualitative Validation

I used in-depth interviews to validate the computer models developed in chapters 4 and 5. Through these interviews, I obtained field expert thoughts on how my computer simulation models reflect the reality of their processes. The interviews validated questions I had in analyzing existing organizational data presented in chapter 5.

Two types of error are encountered when performing in depth interviews: (1) sampling and (2) measurement error. A brief description of these types of errors is provided below.

1. Sampling error occurs when researchers interview only a subset of the available population (Salant and Dillman 1994). This error is intrinsic to the sampling process. One way to reduce sampling error is to increase the sample population, but error can never be eliminated unless the total population is interviewed. This would not be feasible in this work. I had access to a limited number of OSHPD officials that were willing to work and provide feedback but could not possibly contact all (200+) OSHPD personnel. However, the ability to estimate with a fair amount of accuracy the central tendency of a population by obtaining data from only a small portion of the population is what distinguishes interviews from all other research methods (Dillman 2007).
2. Measurement error occurs when respondents of questions provide inaccurate, imprecise or incomparable answers. Two sources of measurement error exist.
   2.1 Measurement error can be due to the interviewer, e.g., leading the respondent by suggesting an answer. For example: "Rework is a major source of motivational and productivity impacts. Don't you think that is right?" This error can be reduced by carefully scripting out what the interviewer says.
   2.2 The respondent can add to measurement error. An example commonly occurs when asking for salary information. A simple question such as "What was your

annual salary last year?" can provide many different answers. One respondent may not think this is relevant and may answer zero or $5 million, both answers may be true but it is more probable, that the answers provided are incorrect. These answers are typically noted as outliers and may be eliminated from the data set when reviewed by the researcher. The best mitigation technique for respondent error is to write clear, concise, and unambiguous questions that people can and want to answer (Salant and Dillman 1994).

This research uses a focus group to acquire a general understanding of the impact that rework has on the design and construction industry. A focus group is a small subset of the target population including individuals who can provide ideas about the topic (Salant and Dillman 1994).

The interviews consist of open-ended questions that leave the answer entirely up to the respondent. An example in this research would be "What is the major cause of rework that you encounter?" This type of question can provide broad answers. The strength of an open ended question is that it allows the respondent to provide their own input which the researcher may not have anticipated. When compared to structured questions, open ended questions offer a greater amount of answer diversity.

## 1.7 Dissertation Structure

Figure 1-7 shows the six additional chapters of this dissertation.

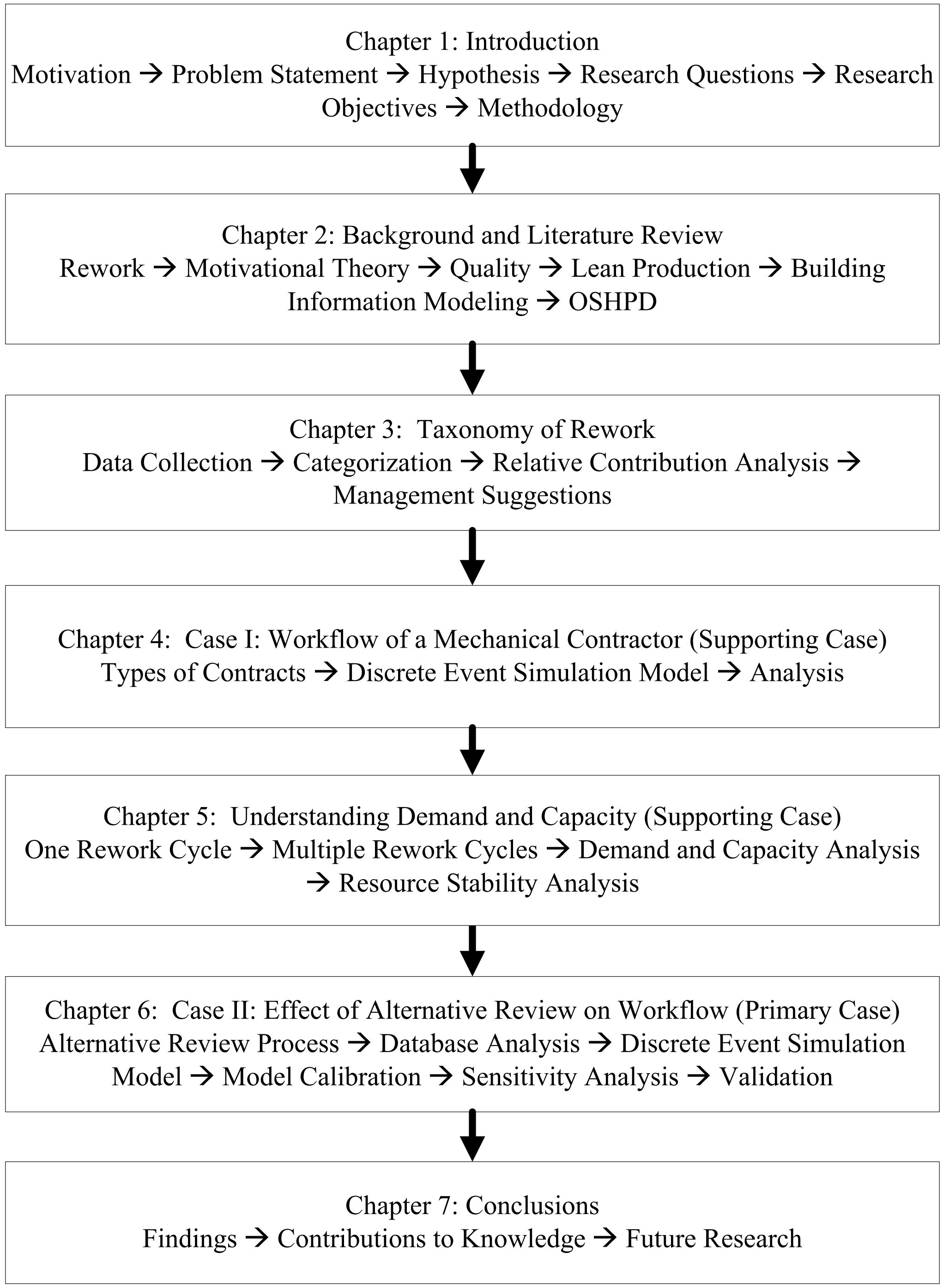



Figure 1-7 Dissertation Structure

Chapter 2 titled "Background and Literature Review" consolidates the relative literature needed to support the research effort. It contains information on what rework, lean, quality, motivational theory is and related research that has been conducted by others.

Chapter 3 titled “Taxonomy of Rework” analyzes data obtained from a series of industry workshops to determine the current state of design and permitting in the healthcare facility construction industry. It takes a number of rework occurrences and categorizes them using an existing multi-tiered framework. This chapter describes the causes of rework that exist and the need to improve the current state of delivering healthcare facilities. This chapter will help to answer research question one.

Chapter 4 titled “Case Study I: Workflow of a Mechanical Contractor” illustrates complexity in the design and permitting of healthcare facilities from the point of view of one discipline, the mechanical contractor. It describes the pressures on the system, and why in many situations drawings are submitted for review before they are completely done. It illustrates that it is possible to use computer modeling (specifically using discrete event simulation) to describe workflow through an organization. This will help to answer questions two and three.

Chapter 5 titled “Understanding Demand and Capacity Using Simulation” illustrates the complexity rework adds to a simple production system. This production system explores three throttles that influence lead time, queue size, and system stabilization, namely: (1) inflow, (2) review resources, and (3) the likelihood of rework. A series of simulation models were created to provide intuition on how the three throttles can be controlled. This chapter illustrates the tradeoffs that must be made to balance demand and capacity under the pressure of increasing rework. This chapter will help to answer questions two, three, and four.

Chapter 6 titled “Case Study II: Effect of Alternative Review on Workflow” analyzes the workflow of OSHPD. It describes their current state process and how the future state process may be affected by implementing an alternative way of reviewing drawings with the paradigm shift of avoiding the embedding of errors early. This chapter is linked to chapters 3, 4, and 5 because it extends computer modeling of an organization. It also shows that by implementing an alternative review process many causes of rework revealed in chapter 3 can be eliminated. This chapter will help to answer questions two, three, four, and five.

Chapter 7 titled “Conclusions” wraps up the efforts conducted in this research. It provides management suggestions, presents research findings, and consolidates the contributions to academic knowledge. Chapter 7 ends with additional research questions that surfaced from conducting this research.

# 2. BACKGROUND AND LITERATURE REVIEW

The literature review presented here in chapter 2 has three main topics covering (1) rework, (2) motivation, and (3) quality as shown in figure 2-1. The purpose of figure 2-1 is to present literature that supports the research described in chapters 3, 4, 5, and 6. This figure shows the topics that classify rework in the AEC industry and how lean production theory can be implemented and studied through simulation modeling. Figure 2-1 starts with "causes and effects of rework on the delivery of healthcare facilities in California" and explores the literature through costs, classification, and rework descriptions. Ng et al. (2004) and Love et al. (2000) studied the direct cost of rework through contract costs.

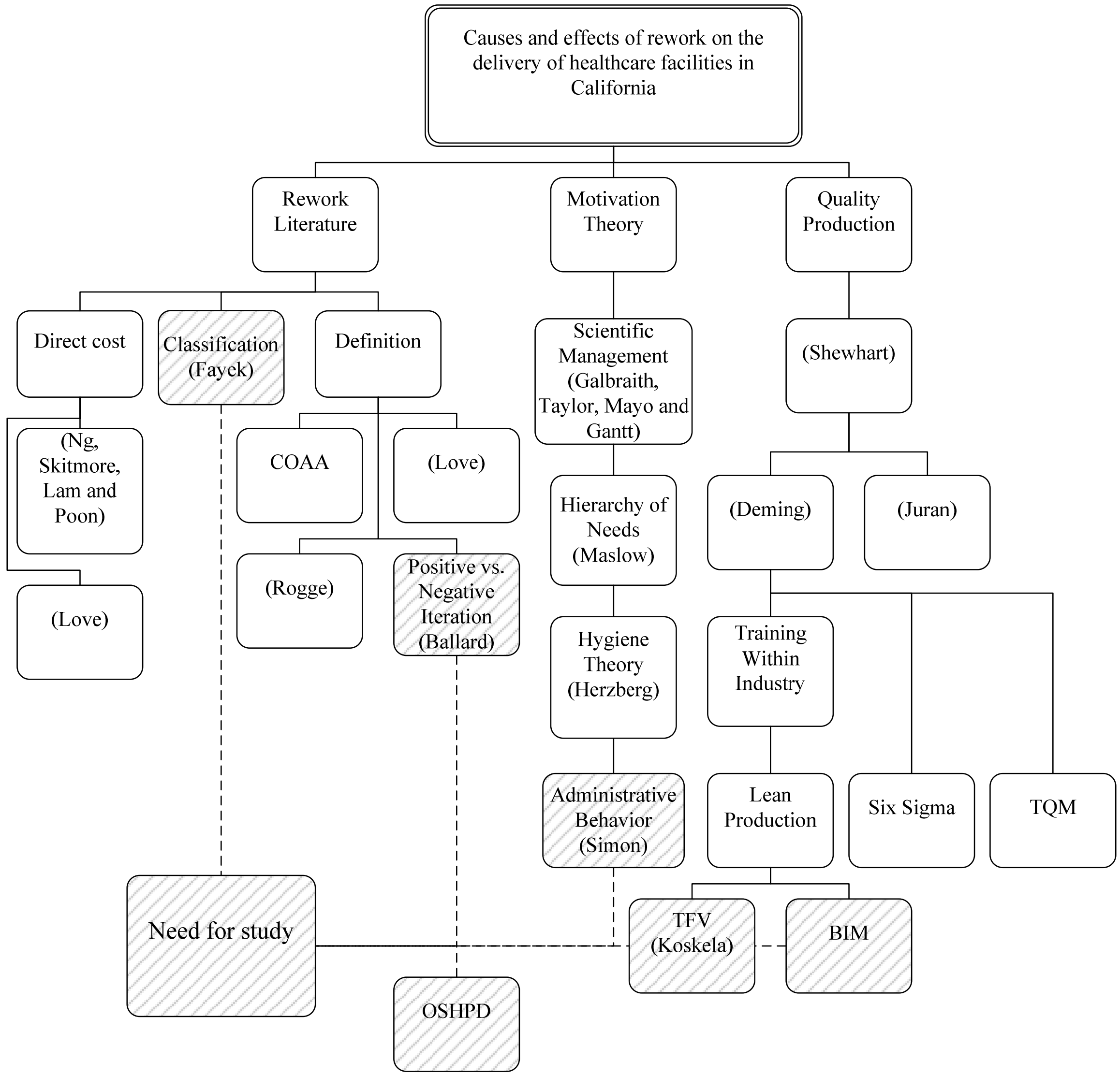



Figure 2-1 Map of Research Literature

Defining rework provides a foundation for the research presented in this dissertation. A literature review provided many definitions of rework; however, the four shown are the most appropriate for work within the AEC industry. The definition developed by Ballard (1999) describing both positive and negative (iteration) rework is used in the research presented in subsequent chapters.

Many different ways to classify rework exist within any industry; however, Fayek's work is specifically tied to the AEC industry. Other types of rework are described in section 2.1.1. However, Fayek's work is concentrated on classifying rework that occurs within the physical construction of the facility. The research presented in chapter 3 attempts to extend Fayek's work into the design and permitting phase of healthcare facilities.

A historical approach is used to describe the transformation of motivational theory throughout the 20$^{th}$ century. It starts with scientific management and follows through to more contemporary management theories developed by Simon (1946). His theory of "satisficing" and bounded rationality are used to frame how industry members within the AEC industry behave. Section 2.2 provides additional information on this topic.

Understanding the history of the quality movement is also necessary as a foundation to this research. One specific topic of lean production is used extensively, specifically the theory of transformation, flow, and value (TFV) developed by Koskela (1992) is used as a way to understand facility construction. This theory is used in chapter 4 and 6 to describe how a change in management decisions affects organizational workflow.

Understanding building information modeling (BIM) and its ties to the AEC industry are important to the research presented in chapter 6. BIM is a tool that aides the development of design drawings. The research presented in this dissertation is supported by three topics required to accomplish the work, (1) building information modeling (BIM), (2) discrete event simulation, and (3) Office of Statewide Health Planning and Development (OSHPD).

The solid lines in figure 2-1 represent direct links of research that have been accomplished in those areas. The dashed lines from the hatched boxes represent work that needs to be explored. As shown, research in classifying rework and modeling workflow needs to be explored further.

## 2.1 Rework

Negative rework is the focus of this research. Ballard (1999) defined 'negative rework' as that which "can be eliminated without loss of value or causing failure to complete the project." An example of negative rework occurs when a plumbing system fails pressure testing and has to be removed and modified, while an example of positive rework occurs when participants in the design process leave with a better understanding of customer requirements when an item of work is re-accomplished.

Negative rework is costly and wastes time especially from a lean perspective where the target is rework elimination. The current literature on rework in general includes work in quantifying the direct cost of rework (Ng et al. 2004, Love 2002): it targets the cost that was incurred because of incorrect installation procedures or owner required changes and does not adequately address how to avoid rework. The research presented in this dissertation focuses on the impact of eliminating rework in organizational workflow.

### 2.1.1 Rework in the Computer Industry

Rework is a phenomenon that occurs in other industries as well. For example in the computer software industry it has been classified into three types: (1) evolutionary,

(2) avoidable retrospective, and (3) avoidable corrective. Table 2-1 characterizes these types of rework.

| Type of Rework | Characteristics | Comments |
|---|---|---|
| Evolutionary | Work performed on a previous version of an evolving software product or system to enhance and add value to it | This is good if it adds value without violating a cost or schedule constraint |
| Avoidable Retrospective | Work performed on a previous version of an evolving software product or system that developers should have performed previously | This may be good if small amounts are dealt with now instead of later. However, if excessive, it indicates a need to revise work processes |
| Avoidable Corrective | Work performed to fix defects in the current and previous versions of an evolving software product or system | This may be good if total rework is kept within control limits |

Table 2-1 Types of Rework - Software Industry (adopted from Fairley and Willshire 2005)

In the software industry, Fairley and Willshire (2005) claim that rework is a given phenomenon, is needed for quality, and ranges between 10 to 20 percent of the total effort, which includes all three types of rework mentioned in table 2-1. In other words, the 10 to 20 percent includes both positive and negative rework. They discuss the importance of keeping rework within control limits based on statistical process control (SPC). SPC monitors the process using control charts to understand the variation of recurring events. However, SPC is ineffective in improving unstable processes. In their work, evolutionary rework can be linked to positive rework while the two avoidable types of rework can be linked to negative rework. From the lean perspective, negative rework should be eliminated at all costs and is not seen as inherent to the process. This perspective requires and forces a change in organizational relationships because negative rework must be actively pursued, corrected, and eliminated versus hidden, covered up, and not mentioned.

### 2.1.2 Rework in the Construction Industry

Many sources of rework have been identified in the construction industry. A cause and effect diagram (figure 2-2), shows the causes of rework in the construction phase of a project. It shows five main causes of rework: (1) human resource capability, (2) leadership and communication, (3) engineering and review, (4) construction planning and scheduling, and (5) material and equipment supply.

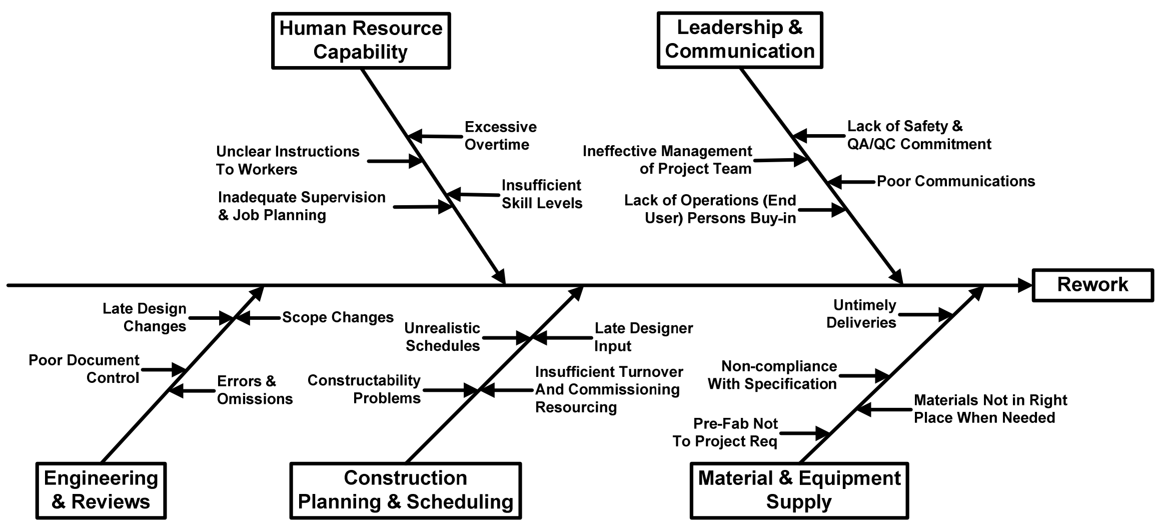



Figure 2-2 Causes of Rework in Construction (Fayek et al. 2004)

The work presented in this dissertation defines the five main causes of rework in the following manner.

1. Human resource capability categorizes rework that deals with the capabilities of the engineers, contractors, and subcontractors that are involved with the project. Untrained personnel working on a facility can lead to rework.

2. Leadership and communication includes the management of the project team and information flow to and from the field workers. Also included is how the project will be checked for quality.
3. Engineering and review has four subcategories of poor document control, errors and omissions, late design changes, and scope changes. This category deals with the causes of rework that pertain to the decision making and flow of information within the discipline engineers and the owner.
4. Construction planning and scheduling categorizes rework within the construction project management phase of the process. The facility is in the construction phase and inappropriate processes are categorized in this rework cause.
5. Material and equipment supply categorizes rework that applies to the physical items that make up the project. It includes incorrect ordering and incorrect timing of when materials are to be received at the project site.

Hanna (2002, 1999, 1997) researched rework occurring within the mechanical and electrical trades to understand the direct cost impact of construction changes. He concentrated on quantifying whether or not a project was impacted by change orders. Hanna identified an impacted project as one where change orders have a negative effect on labor productivity on the base contract. His research utilized a pilot study and quantitative surveys. His survey focused on three areas (1) general background questions, (2) on-budget project questions, and (3) over-budget project questions.

Hanna collected actual and estimated manpower loading curves or weekly labor hours for each project in the survey along with associated change orders. He summarized the factors that affect a project in the planning, design, and construction phases. In the planning phase, a larger project is more likely to be impacted by change orders than smaller projects. In the design phase, impacted projects averaged 50% of their change orders from design problems as opposed to un-impacted projects averaged 38% of their change from design problems. In the construction phase, when overtime and over-manning were used to compress or accelerate the project due to change orders, the project is likely to be impacted. In addition, when absenteeism and turnover were high, the project would be impacted by an increase in change orders. Hanna (2002) drew this conclusion from a series of questionnaires disseminated to 200 randomly selected electrical contractors throughout the United States. The questionnaire had three sections: (1) company specific information, (2) project specific information, and (3) change order information. The first gathered information on the company details. The second collected data from projects they were willing to submit. The third collected the impact of change orders on the projects provided in section 2.

Hanna's research provides a framework to understand some of the factors that can impact productivity during the construction of a project. Many of these impacts were due to design issues. Driving out errors in the design phase improves construction phase productivity.

Many types of errors exist, for example, Hirano and Shimbun (1989) describe 10 categories of errors.

1. Forgetfulness errors occur when the operator is not concentrating on the task at hand.
2. Errors due to misunderstanding occur when a person makes a wrong conclusion without knowing all of the required information.

3. Errors in identification occur when a decision is made without seeing the entire situation at hand.
4. Errors made by amateurs occur through the lack of experience.
5. Willful errors occur when an individual decides to ignore the rules under certain circumstances.
6. Inadvertent errors occur when a mistake is made without knowing how they occurred.
7. Errors due to slowness occur when actions are slowed down by delays in judgment.
8. Errors due to lack of standards occur when no clear instructions on how to accomplish the task at hand exist.
9. Surprise errors occur when items perform in an unexpected manner or outside operating parameters.
10. Intentional errors occur when people make mistakes on purpose to sabotage the process or product.

This is only one such list of categories, many more exist but in the end, it is the view point of the researcher of this dissertation that most if not all errors can be prevented if the time is taken to identify, investigate, correct, and learn from errors.

A tenet of lean is to work towards one piece flow where an item can be produced almost instantly without inventory. This lean ideal situation may not be realizable, but reducing workflow batch sizes reduces errors. The following research discusses a potential scenario on how to evaluate batch sizing within a manufacturing setting. This work is carried over to the research presented later, which reduces the batch sizes of design drawings to ensure errors are not embedded into healthcare facility design.

### 2.1.3 Optimizing Batch Sizes and Rework

In Lean manufacturing, reducing batch sizes is one way to increase flow and quality. Inderfurth et al. (2005) studied the effect of batch sizes on rework and product deterioration in a production system. Their work determined how many units should be produced prior to switching over to completing rework items taking into consideration setup times and product deterioration. Their research developed a static deterministic lot-size model for a single product, which focused on a two-stage manufacturing system. Figure 2-3 shows the basic structure of the model they used to evaluate the optimal lot size. Their goal in optimization is to minimize the total cost per unit time. Using this model, they determined that the rework cost per unit time was linearly related to the production lot size. They concluded that the relationship of per unit holding costs for reworkable items has a major influence in determining the optimal lot size. The research explored in this dissertation uses the theory of reducing batch sizes presented by Inderfurth et al. (2005). However, it does not utilize the optimization of rework per-unit time; instead, it focuses on driving out the errors that exist due to the exchange of large batches of design drawings in healthcare facility construction.

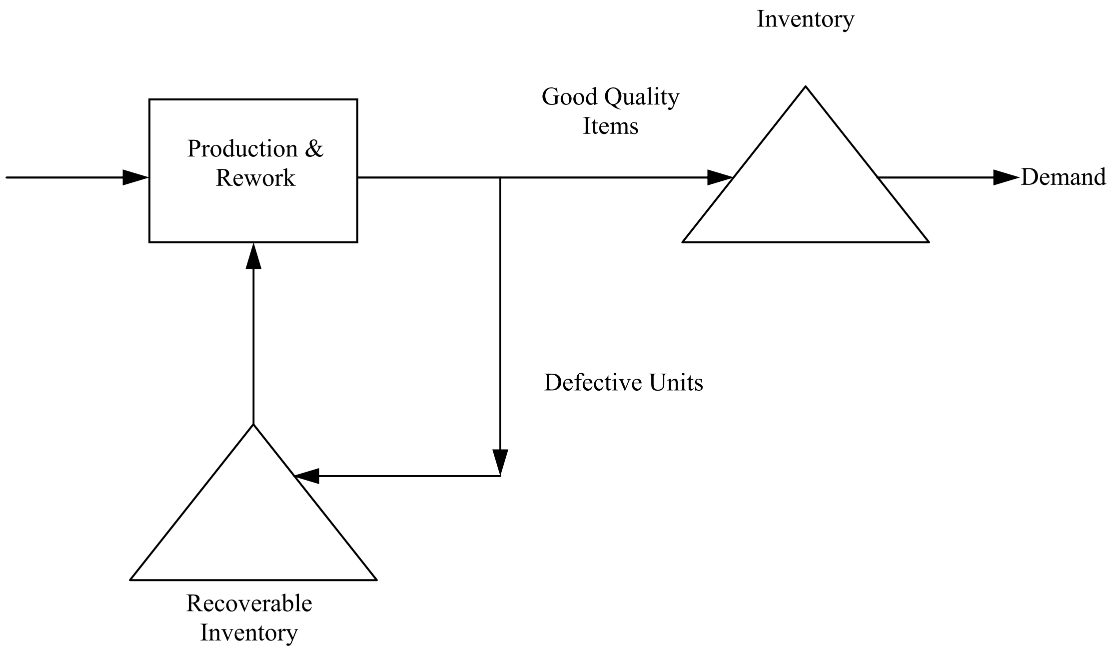



Figure 2-3 Schematic Structure of the Production System (Inderfurth et al. 2005)

Buscher and Lindner (2007) developed a simulation model to optimize a production system by varying rework and batch sizes. The work focused on minimizing economic cost and rework quantity by determining batch sizes for production and rework. The model used is similar to Inderfurth et al.'s in that it used a static deterministic lot-size model for a single product using a two stage manufacturing system where both production and rework occur. They found the production and rework sizes can be determined simultaneously. They determined that the cost of rework is directly related to the lot size and concluded that a policy of fabricating two items prior to performing a rework lot in manufacturing should be a pre-specified policy.

What is clear from these two examples of simulating rework in production is that rework is taken as a given phenomena much like in the computer industry. However, I take the viewpoint that rework is avoidable, e.g., by reducing batch sizes to ensure errors are not embedded into design drawing early in the process thereby precluding downstream errors from occurring.

### 2.1.4 The Liar's Club

Rework has been researched with respect to concurrent product development. The move by many industries towards concurrent product development is predicated on the need to bring products to market earlier and deliver facilities on a compressed schedule. Developing products faster than your competitors can increase market share, profit, and a long-term competitive advantage (Wheelwright and Clark 1992, Meyer 1993, Patterson 1993). Concurrent development has been shown to dramatically reduce cycle times but has proven difficult for many to implement (Backhouse and Brookes 1996, Wheelwright and Clark 1992, Womack et al. 1990, and Nevins and Whitney 1989). Concurrent development increases the frequency and the number of handoffs between project phases, which increases complexity. More tasks are started with incomplete or preliminary information which increases the amount of rework (Ford and Sterman 2003).

In many situations the project stays on schedule until 90% completion and it then stalls, leading to schedule delays; Ford and Sterman (2003) call this situation the 90% syndrome. A senior manager in one company noted "the average time to develop a new product took approximately 225% of the projected time plus or minus 85%. We can tell you how long it will take, plus or minus a project (Ford et al. 1993)." The 90% syndrome is common in the software, construction, consumer electronics and semiconductor industries (Abdel-Hamid 1988, Demarco 1982, Kiewel 1998).

One practice contributing to the 90% syndrome is the practice of concealment, or what Ford and Sterman (2003) call the “liar’s club.” The liar’s club refers to an organization where concealment is standard practice. Project managers of subsystems hold information back on what their real schedule is and how much rework they encounter and push downstream. Project teams hold information in hopes someone else among the project teams will eventually have to come forward and state they are behind schedule. Then the rest of the project team can add time to their schedules allowing them to cover up errors. Such practices extend the completion time and produce the 90% syndrome. This situation occurs in construction projects in part due to the multiple handoffs between the project players. Each player says they are on schedule yet may be behind—hoping to find time to correct errors—and delaying the release of more complete information.

Managers conceal information for six reasons (Ford and Sterman 2003): Concealing

1. Reduces the need for iteration (temporarily), which increases leaderships’ perception of schedule completion. This occurs because the typical management perception of any iteration is negative which it does not need to be.
2. Allows downstream players to continue to work and therefore reduces the pressure of the upstream player to release work faster. If a downstream player is not receiving enough work, they could raise it to leadership’s attention which would then focus the spotlight onto the upstream player. Leaders in this culture avoid this at all costs even if errors are known to be present.
3. Reduces the amount of known work that needs to be reworked and further coordinated, improving apparent project quality.

4. Delays coordination so that rework spreads the work over a longer period of time, reducing peak resource needs.
5. Leads to rework that increases the chance that schedule delays by other phases will allow managers and engineers to solve their own issues.
6. Enhances the manager's job security because leadership will not be focused on their work.

Ford and Sterman (2003) developed and simulated the effect concealment had on a project. They determined increasing concealment:

1. Significantly lengthens project durations, increases cost, and reduces quality.
2. Leads to smaller cycle time reductions experienced by concurrent development.
3. Has a greater impact when high concurrence occurs because more work has been done with errors that are concealed until finally detected at the end of the project. This greater impact is illustrated using a series of simulation models where concealment is varied between 0% and 100%.

Changing the paradigm from phase efficiency to system optimization is a way to mitigate the liar's club and 90% syndrome. Leadership must address both technical and behavioral issues to find a solution to this problem (Ford and Sterman 2003).

Repenning and Sterman (2001) highlighted an issue with organizational culture, namely that people do not get credit for correcting errors that never occur. They conducted in-depth case studies with industries to include telecommunications, semi-conductors, chemical, oil, automobile, and recreational products and found process improvements were quickly abandoned because of process variability. They state that many organizations reward heroes that can come in and fix a process under duress, rather than cultivate a spirit of team members working to consistently improve the process. For example, a mechanical contractor may have to re-detail design drawings multiple times (negative iteration) before the change is finalized. The mechanical contractor must invest additional resources to reconcile design changes and does not get compensated for the additional work or for improving the design (Feng et al. 2008).

### 2.1.5 The Culture of Change

In talking about changes to an organization, the resistance to change must be addressed. Lawrence (1969) discussed the two aspects, (1) technical and (2) social, that must be identified prior to dealing with the resistance to change.

1. The technical aspect to the resistance to change deals with the actual skills that the personnel must have to perform after the change has occurred. For example, personnel will resist a change to a new computer system because they do not have the skills to perform the new computer work and, fearing they will lose their job, will resist this technological change.
2. The social aspect to the resistance to change deals with personnel interactions within the new process. For example, a process change will require regulatory reviewers to meet with and discuss design options with the design team. However, the regulatory reviewer is shy and introverted. Therefore, this new process where they have to interact with the design personnel is foreign to how they work and therefore, they will resist this process change.

Lawrence (1969) makes this distinction to ensure senior leaders know how to deal with the resistance to change and that many times, senior leaders overlook this simple distinction. For example, take the regulatory reviewer in the aforementioned example, even if senior leaders offered the individual more money to work in the new process, they will continue to resist because they are uncomfortable working with the other design professionals. Therefore, to overcome this social aspect, senior leaders will have to provide training to the individual that will make them more comfortable so they can overcome their shyness and introvertedness.

Literature has identified four reasons in which people in an organization resist change: (1) self interest, (2) misunderstanding and lack of trust, (3) different assessments, and (4) low tolerance for change (Kotter and Schlesinger 1979).

1. Self interest is a major resistance to change because people enduring the change fear they will lose something of value. The resistance occurs because people are looking out for their best interests and not for the best interests of the organization. For example, a new technology is introduced to improve production efficiency. However, during this implementation, some personnel will have to be moved to another department. Fearing they will lose their jobs or the value they create, the personnel resist the new technology.
2. Personnel resist change when they do not understand what the impact of the change will be and think that the cost is greater than the benefits they will receive. For example, senior leaders of an organization decide to implement a flexible work schedule to make the organization more attractive to potential employees. Current employees resist the change, because they believe, the new flexible work schedule means they would be on call by their supervisors to work when they are needed the

most. Therefore, the current employees resist the new flexible work policy because they misunderstand the policy tenets.

3. Personnel may also resist change because they assess the potential improvements of the change differently from their supervisors. They see more costs involved with the change, both individually and to the organization, than benefits. For example an organizational executive gets a report that a business unit is producing a toxic waste that is poisoning a nearby town and decides to shut down the department. The only person informed about the toxic waste is the senior plant manager. The plant is going to be shut down and the personnel will be retrained. However, the personnel resist the change because they don't see the benefit of not producing toxic waste.
4. Finally, personnel resist change simply because they have a low tolerance for change. These personnel fear they do not have the new skill or behavior to adapt to the proposed change.

Kotter and Schlesinger (1979) present five techniques to deal with the resistance to change: (1) education and communication, (2) participation and involvement, (3) facilitation and support, (4) negotiation and agreement, and (5) manipulation and co-optation.

1. Use of education and communication is one of the most common ways of dealing with the resistance to change. Simply communicating what the change is and how it will really affect organizational personnel will make great strides in reducing the resistance to change. This education can occur through many types of media, such as one-on-one discussions, group presentations, emails, teleconferencing, memos, and reports. The information presented in this dissertation is one way to reduce the

resistance to change. It will provide insight to how the change can improve organizational process efficiencies.

2. Participation and involvement reduces the resistance to change by including those who will or may resist the change in the design and implementation of the change. Senior leadership listens to the personnel and takes into consideration their concerns with the change.
3. Senior leaders can reduce the resistance to change by providing new skill training or giving personnel incentives after demanding work sessions. This technique to reduce the resistance to change is called facilitation and support.
4. Senior leaders can offer incentives to those that resist the change. This can be in the manner of higher wages for personnel that accept the organizational process changes. This technique is called negotiation and agreement.
5. As a last resort managers can turn to covert attempts to influence others to reduce the resistance to change. These types of managers use selective information to keep power over their personnel so their personnel do not know exactly what the change is and how it will affect them. One form of manipulation is co-optation which occurs when senior leaders offer a new position to those that resist ensuring they are on board with the process changes.

### 2.1.6 Designing vs. Making

Process variation exists in both design and construction and it is important to recognize the differences that exist between the two. Table 2-2 shows a few differences between designing and making.

| Designing | Making |
|---|---|
| Produces the recipe | Prepares the meal |
| Quality is realization of purpose | Quality is conformance to requirements |
| Variability of outcomes is desirable | Variability of outcomes is not desirable |
| Iteration can generate value | Iteration generates waste |

Table 2-2 Designing vs. Making (Ballard 1999)

1. A design is used to make an item; much like a recipe is followed to make a meal. A design exists in the thought processes of individuals while the item exists in the material world.
2. A design is judged against its fitness for use or how well it meets the purpose (Juran and Gryna 1986). Quality of the item is judged by how well it meets the requirements stated by the design, assuming the design meets necessary quality specifications (Ballard 1999).
3. Having variation in design can be desirable, while in making it is not desirable. Hopp and Spearman (2004) distinguish value added versus non-value added variation in design.
4. Iteration in design can generate value for the customer. Such iteration or positive rework in design has been compared to having a good conversation where the players leave with a better understanding of what is required (Ballard 1999). Iteration in making is considered waste because it does not generate value for the customer and should be avoided.

### 2.1.7 Strategies to Reduce Negative Rework

The focus of the research presented in this dissertation is specifically on reducing negative rework. Table 2-3 illustrates some strategies that can reduce negative rework in design.

| |
|---|
| Restructure the design process<br>• Use Design Structure Matrix (DSM) to resequence activities to reduce interdependencies<br>• Use pull scheduling while reducing batch sizes<br>• Work to achieve greater concurrency |
| Reorganize the design process<br>• Make cross-functional teams the organizational unit<br>• Use team problem solving (e.g., call a meeting)<br>• Share ranges of acceptable solutions |
| Change how the design process is managed<br>• Pursue a least commitment strategy<br>• Practice set-based design<br>• Use the Last Planner$^{TM}$ system of production control |
| Overdesign (design redundancy) when all else fails |

Table 2-3 Strategies for Reducing Negative Rework (Ballard 1999)

The research presented in this dissertation focuses on restructuring and reorganizing the design process. Specifically, (1) reducing the batch sizes of design reviews, (2) increasing team problem solving techniques, and (3) implementing a specialized design review team will be analyzed in the alternative review processes. A sensitivity analysis on input parameters will be used to study the impact of these techniques on organizational workflow.

### 2.1.8 Changes Timing

Change often leads to rework and negative rework is wasteful, by definition, if it can be eliminated without loss of value or causing failure to complete the project (Ballard 2000). Changes are identified as any variation from the original project scope (Ibbs 2005), they can either add or deduct from it. Changes can be the responsibility of the owner, the designer, the contractor, or a third party. Changes can occur early in the project, and dealt with immediately or later on in the schedule. Changes can also occur late in the project, and dealt with immediately or later on in the schedule The decision to deal with the change depends on the information on hand and the possible variation of that information. If variation is likely to exist, adopting a set based decision technique is desirable because more options are available for when the decision has to be made. When changes occur, they will affect a project differently based on whether they are dealt with early vs. late in the project; this defines the concept of changes timing.

Figure 2-4 illustrates the concept of changes timing; on the x-axis, "when change occurs" can happen either early or late. On the y-axis, "when change is addressed" can also happen either early or late. A set-based design strategy can alleviate the disruptions when a change occurs early and is addressed early, because a series of designs may solve the change easily. A flexible design is required if a change occurs late and is dealt with early because the project is already well into construction, so if the design is flexible, a change can be easily made. If a change is dealt with late, it doesn't matter if the change occurs early or late, it will most likely result in project delays.

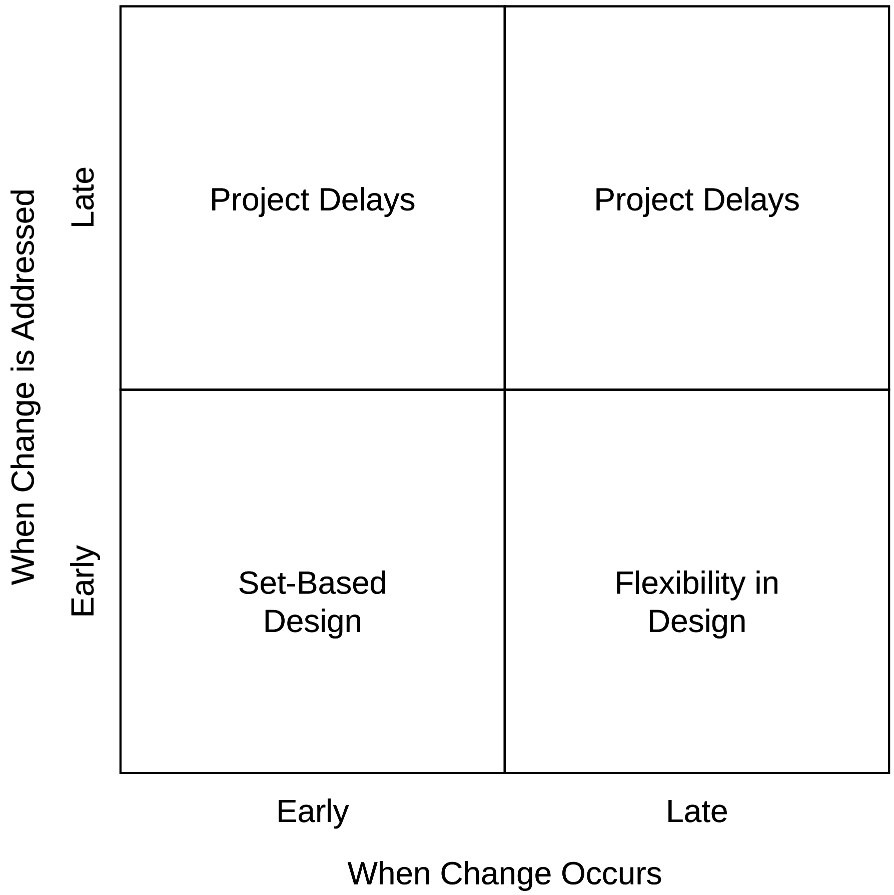



Figure 2-4 Changes Timing

The impact of changes on project delivery has been studied in different ways. Leonard et al. (1991) used 90 cases that resulted in owner/contractor disputes to quantify the effect of change orders on labor efficiency. Change-order impacts were placed in three categories: (1) minor, (2) medium, and (3) high. Ibbs and Allen's (1995) CII report presented data from 89 cases to research three hypotheses: (1) Changes that occur late in a project are implemented less efficiently than those that occur early in a project. (2) The more change exists on a project, the greater its negative impact on labor productivity. (3) The hidden or unforeseeable costs of change increase with an increase in project change. They could not statistically prove hypothesis 1 but determined four critical variables (1) permanent material installed, (2) construction labor for change implementation, (3) engineering labor for change implementation, and (4) total change costs. They were able to statistically prove hypothesis 2 with a 10% confidence level. For hypothesis 3, a ratio of hidden costs divided by the final control budget was developed. Qualitatively, they found most project managers have no process to quantify indirect impacts of change orders and doing so is nearly impossible when multiple change orders are involved.

Hanna et al. (1999) looked at the loss of efficiency of labor productivity through four independent variables and presented a model to estimate the loss of efficiency. Ibbs (2005) studied the impact of changes on project productivity on early, normal, and late timing situations. He found that late changes impact project productivity more than early changes. Therefore, if changes are needed at all, early changes should be encouraged and late changes discouraged. Isaac and Navon (2008) present a change control tool that identified the implication of change. The tool notifies stakeholders if the proposed change has the possibility of delaying the project. This allows the project management team time to reduce the impact of the change.

Changes have a different impact depending on when they occur in a process. The concept of making decisions at the last responsible moment (defined as "the moment at which failing to make a decision eliminates an important alternative" (Poppendieck 2003, Ballard 1999)) affects the impact of changes. Presumably, changes occurring before the last responsible moment in design has been reached, will have less of a process impact than those same changes occurring later. Using the last responsible moment allows decision makers to carry more alternatives forward leaving more time to gather information on each alternative, ultimately allowing for a better decision to be made. For example, a mechanical contractor can carry multiple options for placement of large chiller units in the basement until the final structural column design is finalized. Once column locations are known, a decision on final chiller equipment type and location can be finalized.

Therefore, it is important to drive out potential errors as early as possible. In the case of healthcare facility design, ensuring no errors exist in the layout and fire, life, and safety design is critical to avoid major negative rework later on in design and construction. A way to avoid the embedding of errors is to conduct concurrent design and government review which ensure all parties are in alignment on design decisions which will ultimately reduce negative rework.

## 2.2 Motivational Theory

Motivation of the work force impacts labor productivity. Negative rework and when it occurs not only impacts productivity but also affects motivation. Theories by Taylor, Maslow, McGregor, Vroom, Porter, Lawler, and Ouchi among others describe human factors that influence motivation and productivity (Gaspar 2006). However, research of the construction industry has not taken the perspective of using these motivational theories.

Many motivational theories have been developed throughout history starting with Taylor's scientific management, the Hawthorne studies, Maslow's hierarchy of needs, Herzberg's hygiene theory, McGregor's theory X and Y, Ouchi's Theory Z and then the more contemporary theories of expectancy, equity, and reinforcement.

Taylor's scientific management (1911), focused on process improvement by determining the best way to get the job completed. This theory assumed workers were mainly motivated by money and they needed to be strictly managed by their organizations (Gaspar 2006).

The Hawthorne studies conducted from 1925 to 1932 established that the work environment was important to worker productivity. Paying attention to the worker was a way to improve productivity (Landsberger 1958).

Maslow's hierarchy of needs (1943) discusses the need of workers to work their way up five different stages as shown in figure 2-4. Meeting the first three needs, namely physiological, safety, and social needs, then allowed workers to seek higher needs and eventually reaching self-actualization which means to seek out one's full potential.

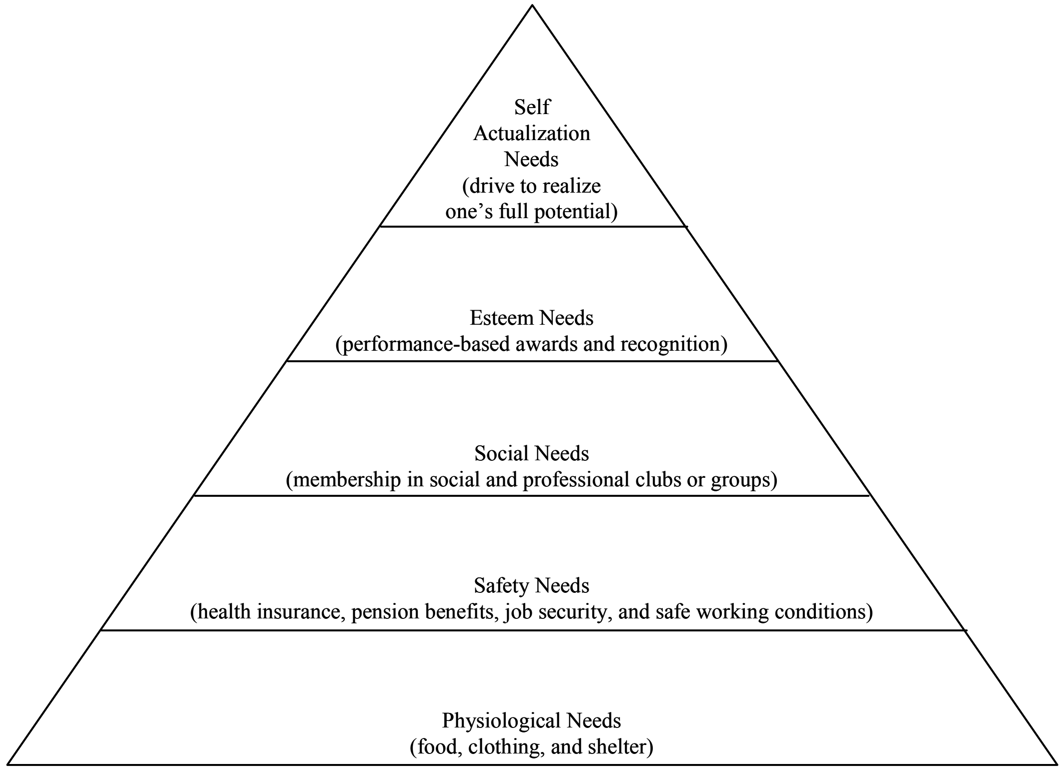



Figure 2-4 Maslow's Hierarchy of Needs (Gaspar 2003)

Herzberg's hygiene theory (1964) posited that job enrichment factors increase motivation whereas hygiene factors de-motivate individuals. The job enrichment factors are (1) achievement, (2) recognition, (3) responsibility, (4) freedom, and (5) advancement. The hygiene factors are (1) work conditions, (2) policies, (3) administrative efficiency, (4) style of supervision, and (5) relationship between employees (Halepota 2005).

McGregor (1967) presented two theories based on juxtaposed situations of human behavior and then discussed which management practices would be efficient in each situation. His theory X presupposes that human laborers are indolent, lack aspiration, and avoid work whenever possible (Halepota 2005). In this situation, management must be extremely strong to control the resources it has on hand. I think this management technique is not functional because the assumptions on human behavior are incorrect. I believe human laborers seek to accomplish quality work as long as it is convenient or makes sense for them to do so.

In theory Y, workers are determined to be hardworking and self-driven which requires a very different type of management style. This theory suggests poor management and manager's policies are the reason why workers do not perform (Gaspar 2006).

In the early 1960's, Vroom developed expectancy theory which states that individual motivation is tied to the individual's perception regarding his or her capability to perform the particular job, the reward associated with it, and the value the individual places on these rewards. The theory puts forth three variables: (1) valence, (2) instrumentality, and (3) expectancy. Valence refers to the attitude an individual has towards rewards whether extrinsic (money, promotion, time off) or intrinsic (self-esteem, fulfillment, satisfaction of a job well done). Instrumentality refers to an individual's perceptions as to whether or not they really get the desired reward. For example, an individual may trust there will be a pay bonus upon completion of work because it was given the last time for good performance. Expectancy refers to an individual's expectations of what is achievable and their level of confidence in completing that task. For example, if a project is extremely difficult and unachievable, a person may not take on the project even if the reward is desired because failure is likely (Vroom 1964). The key idea is: the more attractive a reward is the stronger perception the individual will place on it to succeed (Halepota 2005).

In the early 1980s, Ouchi developed a theory Z that looked at the different types of firms prevalent in the United States and Japan. Type A firms of the United States focused on short-term results, with employees focused on merely achieving greater productivity rates. Type J firms of Japan focused on long-term results, by investing in employees for lifetime employment, focusing on job rotation to allow people to respect others' work, practicing collective decision making, and having a concern for worker welfare. In this theory, Ouchi proposed that firms adopt a little from each of these two firm types in order to evolve a firm that advocates lifetime employment, more specialized career path, and collective decision making allowing all people within the company to participate in managing the company (Gaspar 2006).

An example is the Wallace Company, which won the Baldridge National Quality Award in 1990. The Wallace Company, an industrial distribution company, was known to empower their employees and trained them to improve the quality of each of their processes. They made it known the reward could possibly be the Baldridge award which the workers held in high regard, and which in turn kept them motivated to continue working hard (Braddock et al. 1993). The organization that is the focus of the research presented in this dissertation is also applying for the Baldridge Award; many of their employees are motivated to institute organizational process change to improve the quality of their permitting review and reduce cycle time.

Motivation has been classified into two categories, (1) intrinsic and (2) extrinsic. Intrinsic motivation is driven by an employee's belief that the work itself is interesting, engaging, and satisfying. Extrinsic motivation is driven by financial rewards and formal or informal recognition. Much research has been conducted in the area of intrinsic motivation in an attempt to explain behavior such as exploration and seeking the hardest challenges (Berlyne 1971; Harlow et al. 1950; Hunt 1965; Montgomery 1954; White 1959). Theory has been proposed, stating that self determination and competence are trademarks of intrinsic motivation (Deci and Ryan 1985). These two types of motivation have led to research documenting striking differences in task performance between intrinsically and extrinsically motivated individuals (Amabile et al. 1994).

Simon presented a theory on administrative behavior in 1946. His theory explores how organizations make decisions. Decisions should be correct, efficient, and implementable. Decisions are deemed correct given a specific objective; however, a change in objective implies a change in evaluation of whether the decision is correct or not (Simon 1976). Simon proposes that administrative personnel making decisions in pursuit of self-interests are aware of only some of the possible alternatives, and are willing to settle for an adequate solution rather than an optimal solution. Simon coined this action as "satisficing." In conjunction with his theory on "bounded rationality" which states that people can not know all the information around a decision and therefore, are bounded in some way when decisions are made. He believed humans do not have the mental ability to maximize solutions because we cannot evaluate all outcomes with sufficient precision.

Following are some examples that illustrate "satisficing." One example is the simple task of sewing a button onto a shirt. Let us suppose the best needle to use in this situation is two inches long with a 4 mm eye. This needle is hidden in a box with a 100 other needles varying in size. In "satisficing," the first needle that can sew the button onto the shirt is the one that should be used. Spending the extra effort to search for the optimal needle is a waste of energy.

Another example of “satisficing” occurs when you enter a convenience store looking for a Red Bull energy drink. After searching the entire store, you are unable to find it and eventually decide to buy a Gatorade. You are satisfied with this choice because searching any further is again a waste of time and energy.

A final example of “satisficing” occurs in consensus building when a group of individuals looks to a solution that everyone can live with. For example, a healthcare facility owner team is trying to determine what the budget for a new healthcare facility should be. The team spends hours determining what the revenues will be from different services provided. Eventually, the team reaches an agreement on the budget for the healthcare facility but one person questions if one of the revenue streams is correct. When the group becomes upset with this question they decide to keep the number, not because the person was wrong in raising the point, but rather, they have converged on an acceptable solution and decided it is good enough.

The research presented in this dissertation uses administrative behavior as a foundation of how decisions are made within organizations. Decisions made during the design of a healthcare facility are made in a “satisficing” manner. This occurs because of project constraints such as cost, location, materials, equipment, and other design disciplines. Therefore, design engineers may make concessions on optimal designs because of these project constraints. However, in many situations this satisficing is done without all the necessary players involved in the decision. For example, in many healthcare facility designs, the layout, exiting, fire, life, and safety layout are completed by the owner, architect and structural engineer without consulting the government reviewers. Then, as the design proceeds ahead, while the previous decisions were “satisficed,” they do not meet code requirements and therefore must be reworked. This is negative rework and should be eliminated.

## 2.3 Quality

The work of Shewhart, Deming, Juran, and the Training within Industry effort have been extensively researched and applied to manufacturing processes (Gaspar 2006, Dinero 2005). This work led to the development of the Toyota Production System which has become an icon for manufacturing processes.

### 2.3.1 History of the Quality Movement

The quality movement to improve production capability began in the early 1900s through the work of Shewhart and continued through Deming and Juran. Shewhart is known as the “father of statistical controls” and was the originator of the Plan, Do, Check, Act (PDCA) continuous improvement cycle. This cycle was renamed to Plan, Do, Study, Act (PDSA) and has created many other continuous improvement cycles like Observe, Orient, Decide, Act (OODA) and Define, Measure, Analyze, Improve, Control (DMAIC) which is the basis for Six Sigma. Many organizations have adopted the OODA cycle, especially the military which has incorporated it into military tactics. A former Chief of the Staff of the Air Force, General Moseley mentioned that air power and reconnaissance capabilities allow the US military to get inside an enemy’s OODA loop, allowing the US military to shape the battlefield through improved decision analysis.

### 2.3.2 Deming's Fourteen Points

Deming taught the Japanese project management techniques after World War II (between 1950 and 1965) which allowed them to become a major manufacturing powerhouse in the global economy. His 14 points focuses on long-term improvement for all organizations. They are necessary for an organization to survive and should be presented to the entire organization. Deming's 14 points are (Deming 1982):

1. "Create constancy of purpose towards improvement." Replace short-term reaction with long-term planning.
2. "Adopt the new philosophy." The implication is that management should adopt his philosophy, not only the workforce.
3. "Cease dependence on inspection to achieve quality." If variation is reduced, inspection of manufactured items for defects is not needed, because there won't be any defects.
4. "Move towards a single supplier for any one item." The use of multiple suppliers leads to variation of delivered supplies.
5. "Improve constantly and forever." Constantly strive to reduce variation.
6. "Institute training on the job." If people are inadequately trained, they will not all work the same way, and this will introduce variation.
7. "Institute leadership." The aim of supervision should be to help people and machines and gadgets do a better job.
8. "Drive out fear." Deming sees management by fear as counter-productive in the long term, because it prevents workers from acting in the organization's best interests.

9. "Break down barriers between departments." Another idea central to Total Quality Management (TQM) is the concept of the 'internal customer', each department serves not the management, but the other departments that use its outputs.
10. "Eliminate slogans, exhortations, and targets for the work force asking for zero defects and new levels of productivity."
11. "Eliminate management by objectives." Deming saw production targets as encouraging the delivery of poor-quality goods.
12. "Remove barriers to pride of workmanship." Many of the other problems outlined reduce worker satisfaction.
13. "Institute education and self-improvement."
14. "The transformation is everyone's job."

Deming's third point of ceasing the dependence on inspection to achieve quality is a major tenet in this dissertation. As I illustrate in chapter 6, in many instances the regulatory agency's reviews are viewed as an inspection process thatcauses many delays in the permitting process. Implementing a new process where inspection is less relied on, while still producing quality drawings, is a major point of this work.

### 2.3.3 Pareto Principle

Juran is known for his focus of training top- and middle managers on the idea of quality management; it was imperative to get leadership to "buy-in" to continuous improvement. He also explored the Pareto principle and its application to management requirements. The Pareto principle refers to "80 percent of the problems arises from 20 percent of the defects," but this principle has wider applications ranging from the science of management to the physical world. An example is 20 percent of your stock will take up 80 percent of your warehouse, and 20 percent of your workforce will provide 80 percent of the production. In addition to many of his research interests, Juran explored concurrent engineering, which is a concept where all those involved with design have access to information and the ability to influence the final design in order to identify and prevent future problems (Gryna et al. 2007).

The Pareto Principle is at work within the regulatory agency studied in this dissertation. The review of the largest drawing sets represents a small portion of the incoming work, however, the majority of the agency resources are dedicated to these projects. The majority of work that the agency receives is not a focus of the large healthcare owners or state politicians.

## 2.4 Lean Production

Lean production provides a common structure in which people can discuss ways to analyze, design and control production processes. Koskela et al. (2003) presents three general actions for lean production theory:

1. Design the production system.
2. Control the production system in order to realize the production intended.
3. Improve the production system.

The goals of all production systems are to (1) produce products, (2) reduce costs, time, and materials for the production system, and (3) deliver customer needs based on quality, reliability and flexibility. Therefore, the knowledge and application of this theory should allow practitioners to improve their production capabilities.

### 2.4.1 Three Viewpoints of Production Theory

Production theory has been studied from three different views. The first, the transformation view of production, dominated production theory in the twentieth century. Developed and unchallenged in economics, the transformation view focuses on production as a transformation of inputs to outputs. This viewpoint suggests breaking down the entire process into smaller pieces and then optimizing each step independently of each other step (Porter 1985, Wortmann 1992). The transformation view has two flaws: (1) it does not address other issues inherent in production other than transformation and (2) it does not address customer needs in the transformation when the value of a product must conform to customer requirements (Koskela et al. 2002).

The second, the flow view, strives to eliminate waste from the flow of processes (Gilbreth and Gilbreth 1922). This flow view is central to Lean production, a term developed by John Krafcik in describing the Toyota manufacturing processes (Womack et al. 1990). The flow view uses principles of lead time reduction, variability reduction, and simplification (Koskela et al. 2002). This flow view was adopted by the Japanese for production in the 1940's and has been used in automobile manufacturing by Toyota.

The third, the value view, seeks to maximize the best possible value from the customer's point of view (Shewhart 1931). This theory has been used extensively in the quality movement which uses requirement analysis and systemized flow-down of requirements (Koskela et al. 2002).

Koskela (1992, 2000) recognized that these three views were complementary to each other, yet cause problems in production when one tries to adopt all three at the same time. He argued that they should be integrated, yielding a production theory grounded on the concepts of transformation, flow, and value. The TFV theory of production suggests that modeling, structuring, controlling, and improving production must address all three viewpoints together. (Koskela et al. 2002). This integrated TFV theory of embraces production principles from all three viewpoints, as summarized in table 2-4.

| | Transformation view | Flow view | Value view |
|---|---|---|---|
| Conceptualization of production | As a transformation of inputs into outputs | As a flow of material, composed of transformation, inspection, moving and waiting | As a process where value for the customer is created through fulfillment of his/her requirements |
| Main principle | Getting production realized efficiently | Elimination of waste (non-value adding activities) | Elimination of value loss (achieved value in relation to best possible value |
| Methods and practices | Work breakdown structure, MRP[1], organizational responsibility chart | Continuous flow, pull production control, continuous improvement | Methods for requirement capture, quality function deployment |
| Practical contribution | Taking care of what has to be done | Making sure that unnecessary things are done as little as possible | Taking care that customer requirements are met in the best possible manner |
| Suggested name | Task management | Flow management | Value management |

Table 2-4 TFV Theory of Production (Koskela 2000)

### 2.4.2 Lean Project Delivery System™ (LPDS)

This research effort uses the theory presented by the Lean Project Delivery System™ (LPDS), shown in figure 2-5 (Ballard et al. 2002), that represents the main phases in the life of a project from project definition to end of life. The key difference between

[1] MRP = Material requirements planning

traditional project delivery and the LPDS™ is the relationship between each of the phases and the participants in each phase.

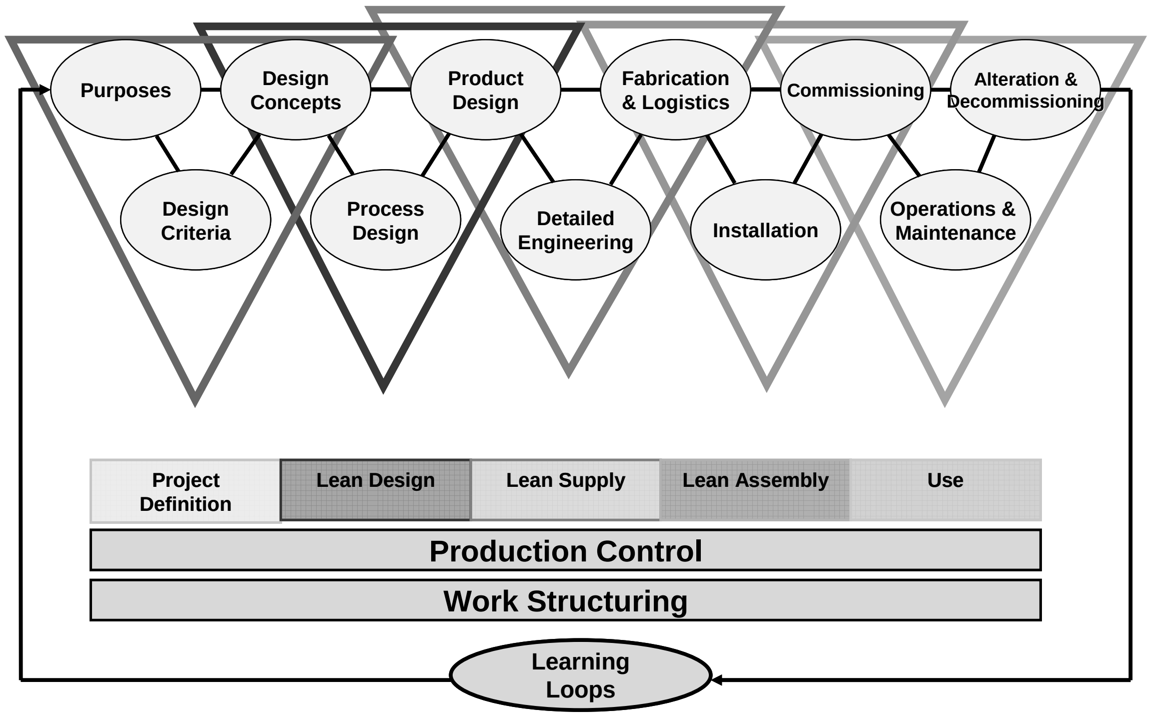



Figure 2-5 Lean Project Delivery System™ (Ballard et al. 2002)

In LPDS, representatives from each of the phases are involved in the decision making process, including members from the production team that designs and builds the facility. Following the concept in line with the LPDS's incorporating product and process together and deferring decisions to the last responsible moment in theory reduces the amount of rework experienced by members of the production system. A fundamental in LPDS is the use of work structuring that integrates product and process together. This concept understands how the actual product will be used in the production phase and ensures that the two complement each other.

The Lean Project Delivery System™ uses some terms not used in traditional project management. The first concept is takt time. Takt is a German word for rhythm or meter. Takt is the rate of downstream demand (Liker 2004). In Lean manufacturing, takt refers to the rate at which the customer is buying the product, i.e. the “pull” of the customer. In production system design takt is used to set the pace of production and inform workers whenever they are getting ahead or behind and all effort is aimed at completing work within the takt time allowed for it. In construction, each phase of work is given a certain amount of time to complete a task with little thought given to how the work is to be handed off to the subsequent downstream player. In construction, large batches of work are released to the following trade. For example, an entire floor or section will be turned over to the finishing crews once the concrete, mechanical, electrical and wall systems are completed.

The second concept is zero defects. In many construction scenarios, zero defects deals with the project at the turnover to the owner or client. Most construction companies are going through punch list items prior to turning the project over as completed. This differs with the concept of zero defects in the LPDS. Lean Project Delivery Systems strive to determine defects as close to when they occurred and then follow through with a root cause analysis to determine what real issue must be addressed and correct immediately.

The LPDS concept of zero defects is used in this dissertation research. Implementation of alternative regulatory agency processes aim to eliminate the error as close to the point of occurrence as possible to ensure after the fact punch list items are avoided.

### 2.4.3 Types of Waste

Lean defines eight major types of non-value adding wastes in business or manufacturing processes (Ohno 1998, Liker 2004).

1. Overproduction - Producing items with no associated orders leads to overstaffing, storage, transportation because of excess inventory.
2. Waiting - Waste occurs when employees are used to watch automated systems or wait on the next processing step.
3. Unnecessary transportation - Carrying work in progress (WIP) long distances, which creates inefficient transportation or moving items into and out of storage.
4. Overprocessing or incorrect processing - Taking unneeded steps to process the parts. When installation is an afterthought to the design of the product field corrections are developed to deal with design issues.
5. Excess inventory - Excess raw material, or finished goods that require transportation and storage costs. Also inventory can get damaged or become obsolete as it sits and waits. In addition, excess inventory hides late deliveries from suppliers, defects, equipment downtime, and long setup times.
6. Unnecessary movement - Wasted motions by the employee whether it is excessive walking or unnecessary reaching for or looking for tools or parts.
7. Defects - Production of defects results in rework, scrap, and replacement production.
8. Unused employee creativity - Losing time, ideas, skills, improvements by not engaging or listening to your employees.

Additional waste items have been identified, such as “making do” - a situation where a task is started without all its inputs, or the execution of a task is continued although the availability of at least one input has ceased. (Koskela 2004)

All of these wastes are part of the processes studied in this dissertation. The presence of defects, especially in the development of design drawings leads to rework that ultimately leads to delays in the process.

### 2.4.4 Working Harder vs. Working Smarter

A systems dynamic model is shown in figure 2-6 that describes the phenomena of working harder vs. working smarter and its impact on process capability. Capability is an investment in resources that create a stockpile to draw from and it degrades over time (i.e., machines wear out, people change jobs). Management increases desired performance over actual performance, thereby creating a performance gap.

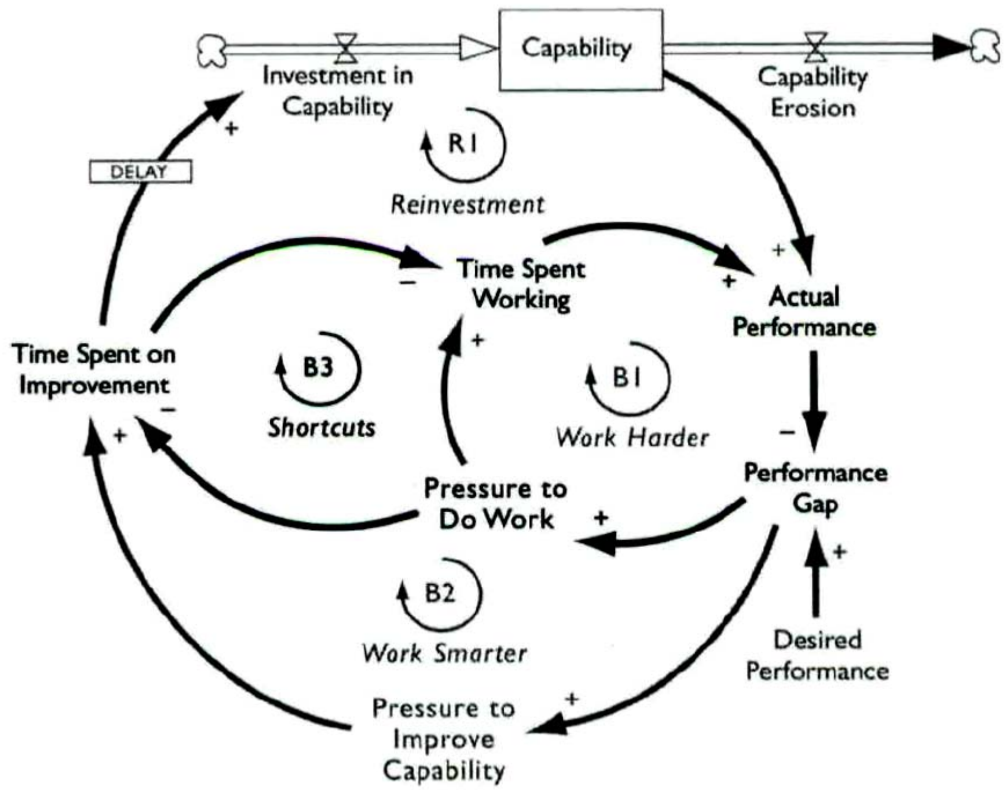



Figure 2-6 Balancing Loop (Repenning and Sterman 2001)

Managers have two ways to deal with this performance gap: (1) work harder, cycle B1, where the manager increases pressure to do work and allocates more time to working which in turn increases actual performance or (2) work smarter, cycle B2, where the manager puts pressure to increase capability and time spent to improve which increases the capability stockpile and actual performance. However, it is important to note the delay in cycle B2 to increase actual performance: where this delay may be quite extensive, managers invest in working harder to get immediate results (Repenning and Sterman 2001).

Repenning and Sterman (2001) conducted simulations using the systems dynamic model in figure 2-6 and produced the system responses in figure 2-7.

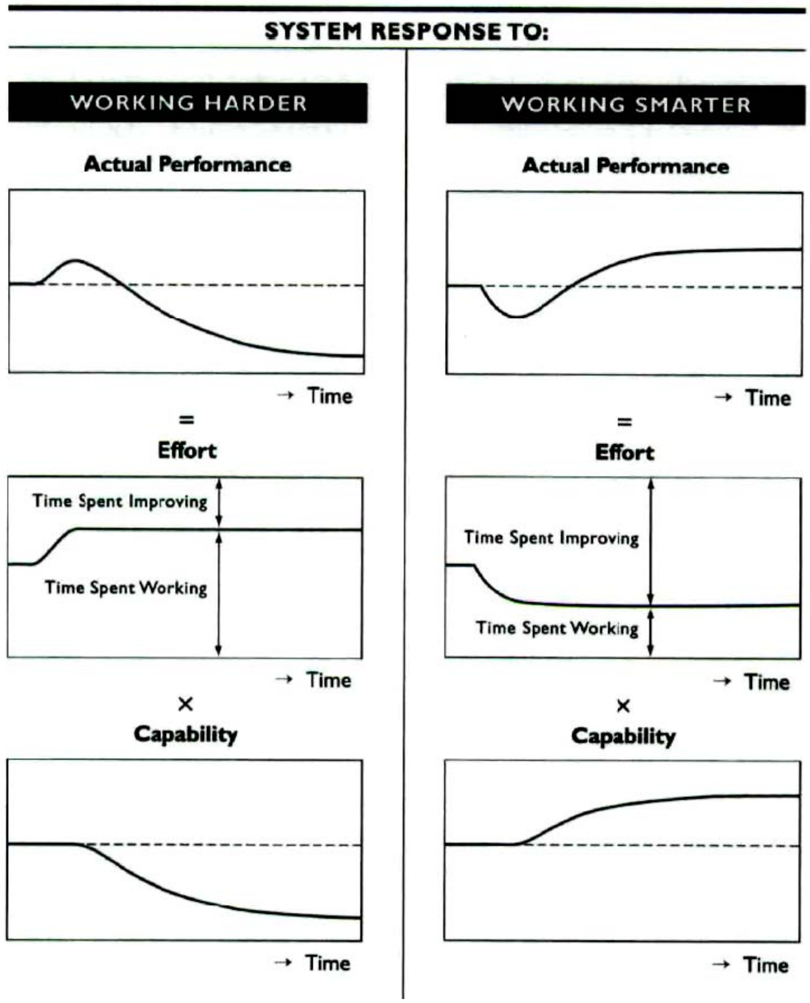



Figure 2-7 Simulation of Working Harder and Working Smarter (Repenning and Sterman 2001)

System performance is based on effort and capability. The first column in figure 2-7, working harder, shows initial performance increases as more time is spent on working and less time on improving capability. However, over time, performance declines as process capability declines. The second column, working smarter, shows an initial dip in performance as more time is developing capability than spent working. However, over time, performance increases as the process capability increases (Repenning and Sterman 2001).

The effect of working harder occurs in the case studies presented in this dissertation. In these situations, organizational personnel must put more effort to get similar results. In turn, due to working harder, the personnel do not have time to improve the system process.

### 2.4.5 Built-in Quality

Built-in quality is a concept derived from the works of Shewhart, Deming, and Juran and is embedded in the manufacturing of vehicles for some of the leading car companies, specifically Toyota Motor Company. The idea of built-in quality is to identify defects as close to the point of origin and design processes that are robust enough to detect during production. The idea of this research is to use the concept of built in quality and standard work to avoid rework.

In the Toyota Production System each member on the manufacturing line has the ability and duty to stop the line if a defect is detected, this is pulling the “Andon” cord (Liker 2004). When pulling the Andon cord, the entire production system will come to a halt if the error can not be corrected within the takt time. When the defect is corrected, the line is again permitted to proceed, however, the root cause of the defect is sought out and corrected immediately.

Another system of built-in quality exists within in the software programming community and it is called Pair Programming. In Pair Programming, software development is taken on by two team members. The team works on only one computer, with one keyboard, where one team member is producing the code, while the other team member is constantly reviewing the work for quality issues. This process has shown to increase quality in the programming design phase and reduces the need for after the fact quality assurance and quality control measures (Winkler and Biffl 2006).

Standard work and control methods for training instruction have been explored to determine its ability to improve production processes (Liker and Meier 2007, Dinero 2005, Mann 2005). They suggest that implementation of these techniques allow and can ensure that quality, cost, and schedule are maintained. Those authors believe that the elements of standard work are at the heart of the quality initiative.

Mistake proofing is an integral concept to lean production. Mistake-proofing is the use of process or design features to prevent errors or the negative impact of errors. It is known in Japanese as poka-yoke, which means to avoid inadvertent errors. Mistake-proofing was formalized into the Toyota Production System by Shigeo Shingo (Grout 2007).

The concept of built-in quality is used in developing a new review process for the regulatory agency to decrease rework. Currently, the agency experiences high rates of rework as discussed in chapter 6.

### 2.4.6 Lean Perspective of Standard Work

Standard work procedures are prevalent in many organizations; however the following quote describes how typical standard work and training occurs in many companies. It is important to note that standard work procedures are not only for the worker but for the supervisor to determine if the work is being done in a prescribed format.

“Every large company has some type of training program in a large variety of area…Yet, go where the actual work is being done and ask people how they learned their jobs and you get a different picture (Liker and Meier 2007).”

This quote describes a situation common to the construction industry, where many people are considered well trained but learn how to build projects without a prescribed method. Typically, each company will have a prescribed way of performing a process, however, these processes are hardly ever an industry standard. Construction projects are known to be custom and different project to project, however, many construction processes are repeated again and again.

One example is batter board installation, which occurs at every construction project. Batter boards frame the extent of a project and is one of the first tasks completed once the site is properly graded. Having a standard work procedure to install batter boards can facilitate and improve construction efficiency. An example of standard work occurs within the Toyota Production System, where the standard work procedures are written on a board that faces away from the workers. The workers know their process, the boards are used by the supervisors to monitor if work is being done by the prescribed format or if workers are deviating from the standard. If the latter, the supervisor must ask why they are deviating. This analysis can lead to better performing procedures which can be documented, disseminated, and repeated. This creates a continuous learning cycle.

Standard work is a foundation to Lean production. The Toyota human development system is a continuous improvement system (figure 2-8). The system has two supporting processes (1) organizational and (2) people. The two support systems each have four parts. Organizational supporting processes are (1) stable employment manpower-management, (2) fair and consistent human relations, (3) recognition and corrective, and (4) hoshin kanri policy deployment. People supporting processes of servant leadership are (1) teamwork, (2) clean and safe workplace, (3) two-way communication and, (4) Toyota way leadership.

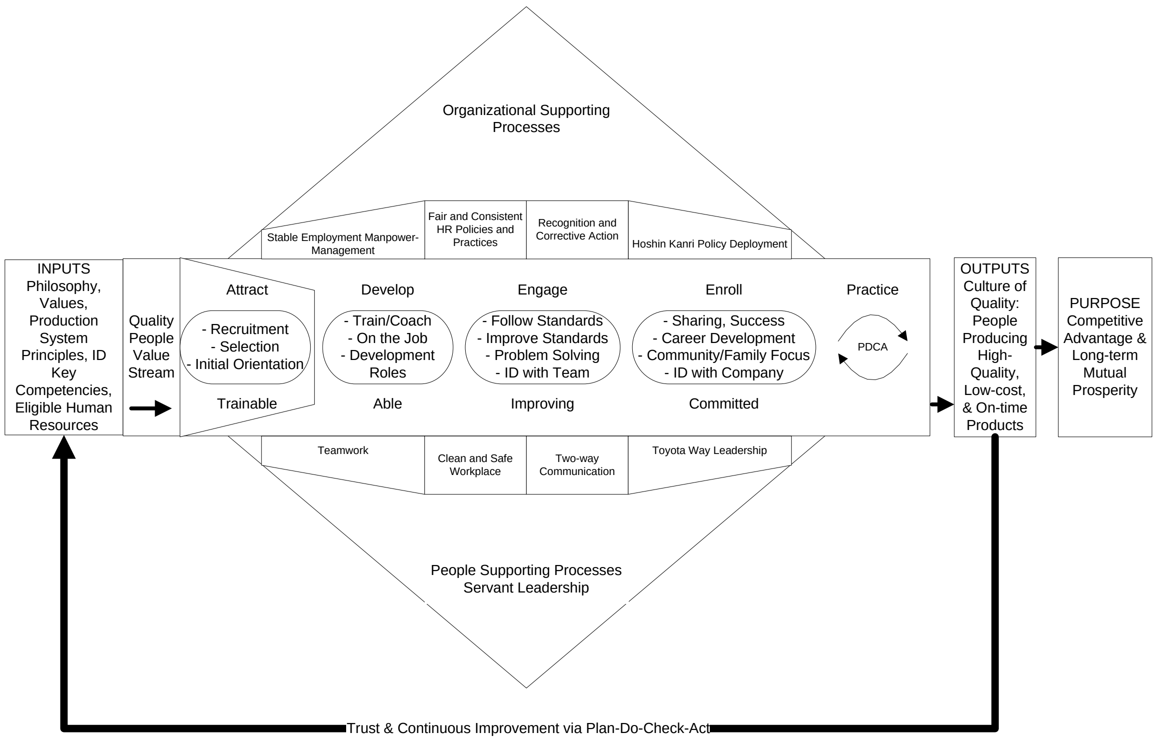



Figure 2-8 Toyota's Human System Model (Figure 2-3 in Liker and Hoseus 2008)

The goal of the human system is to obtain a competitive advantage and long-term mutual prosperity. The human value stream contains five steps: (1) attract, (2) develop, (3) engage, (4) enroll, and (5) practice. In the development phase, training and coaching are primary tasks. In the engagement phase, the standards trained in the development phase are implemented. In the enrollment phase, sharing of what works and does not work from the standards are passed on in the organization. In the practice phase, the standard is implemented and a continuous improvement procedure is followed. Standard work provides a process with less variation which then allows managers to make changes with a baseline in mind. Knowing the baseline process is imperative to understand the impact of process changes.

To develop standard work, it is important to first understand and classify what characteristics are associated with the process in question. A framework for classifying work is presented in figure 2-9.

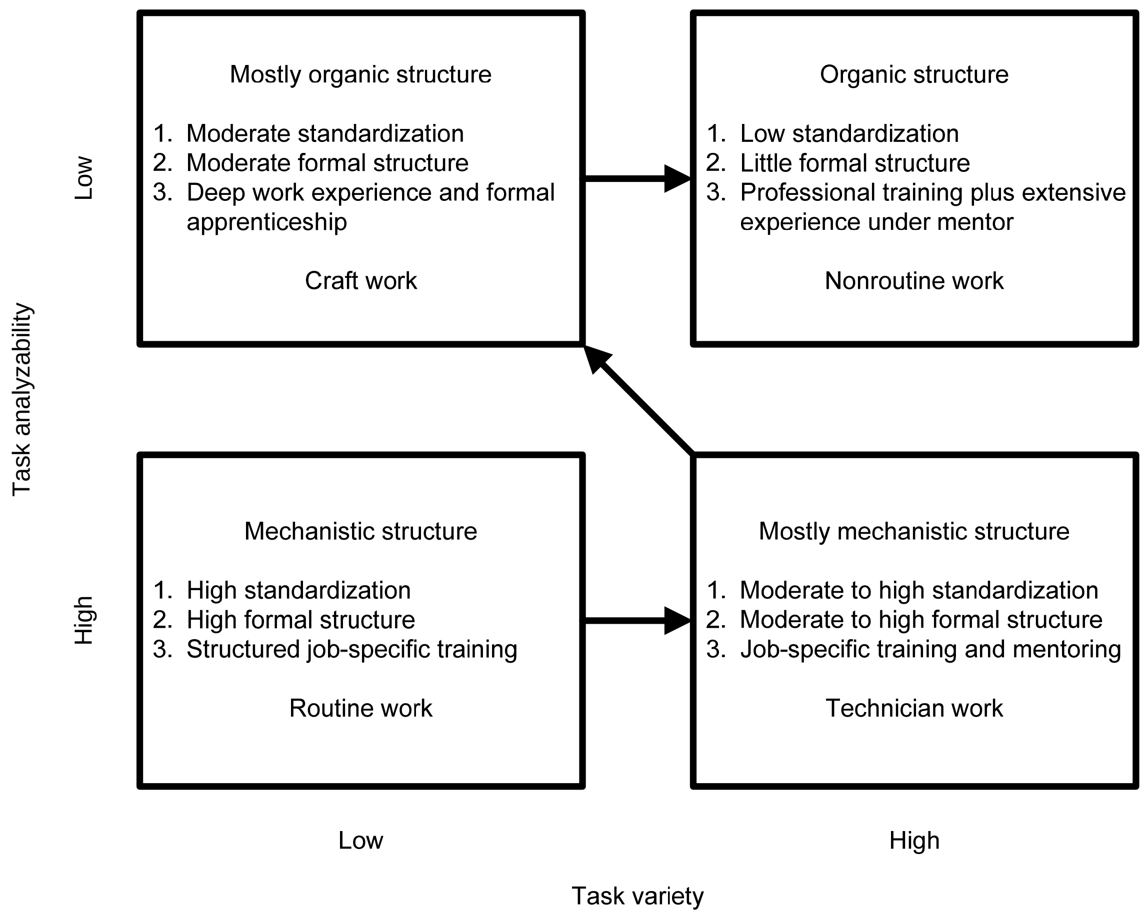



Figure 2-9 Classifying Types of Work (modified Figure 1 in Perrow 1967)

On the x-axis is task variety ranging left to right from low to high. The y-axis is task analyzability ranging bottom to top from high to low. The lower left quadrant represents routine work which has low task variety and high task analyzability. Routine work is done for example by assembly line workers, fast-food servers, bank tellers and data entry clerks as shown in table 2-5.

| Type of work | Example jobs | What can be standardized | Accumulated know-how requirements |
|---|---|---|---|
| Routine (low variety, high analyzability) | Assembly line work, fast food server, bank teller, data entry clerk | Work elements, sequence, timing, fundamental skills, product specifications, workplace layout tools | Recognition of problems, problem response, problem solving |
| Technician (high variety, high analyzability) | Inspection, material handling, lab data analyst, computer technical support work, equipment maintenance | Generic procedures, core processes, fundamental skills, product specifications, workplace layout tools | Troubleshooting ability, intuitive problem solving, mental map of problem situations |
| Craft (low variety, low analyzability) | Group leader, nurse, buyer, some engineering jobs | Generic procedures, fundamental skills, product guidelines, workplace layout tools | Intuitive problem solving, reading situations |
| Nonroutine (high variety, low analyzability) | Program manager, R&D scientist, development engineer, surgeon | Generic procedures, fundamental skills, product criteria, workplace layout tools | Creative-innovative ability, intuitive problem solving, reading situations |

Table 2-5 People Development Requirements for Different Types of Jobs (Table 5-1 in Liker and Meier 2007)

The lower right quadrant represents technician work which has a high task variety and high task analyzability. Examples of technician work are inspections, material handling, lab data analysis, computer technical support work, and equipment maintenance (table 2-5). The upper left quadrant represents craft work which has a low task variety, and low task analyzability. The upper right quadrant represents nonroutine work which is high variety, low analyzability. This research places design and construction within the technician and craft work from lower right to upper left. An example of technician work is brazing copper pipe. This process has high standardization because all copper pipes have the same properties and a proven way to connect copper pipe so it does not leak exists. An example of craft work would be architectural sheet metal for an asymmetric building façade. The requirement for each piece to be individually measured and custom produced requiring much of the workers to have a deep understanding of how the metal and façade interact.

A relationship exists between standardized work and training (figure 2-10). Lean production puts standardized work first then transfers knowledge using the four-step Job Instruction method. The four steps are: (1) prepare the worker, (2) present the operation, (3) try out performance, and (4) follow-up. Standardized work is analyzed to eliminate waste and develop a best method. This becomes a baseline for continuous improvement that is accomplished through task redesign. The best method is transferred to the Job Instruction training program and is taught to employees resulting in consistent performance, results and provides the ability to measure deviation from the best method. The Job Instruction training program includes other skills required by the job and incorporates it in the transfer of knowledge. The Job Instruction method requires that work elements and key points be identified for proper training and this is a continuous cycle with best methods. This cycle resembles a PDCA loop or continuous improvement cycle, which is a common theme in lean production theory.

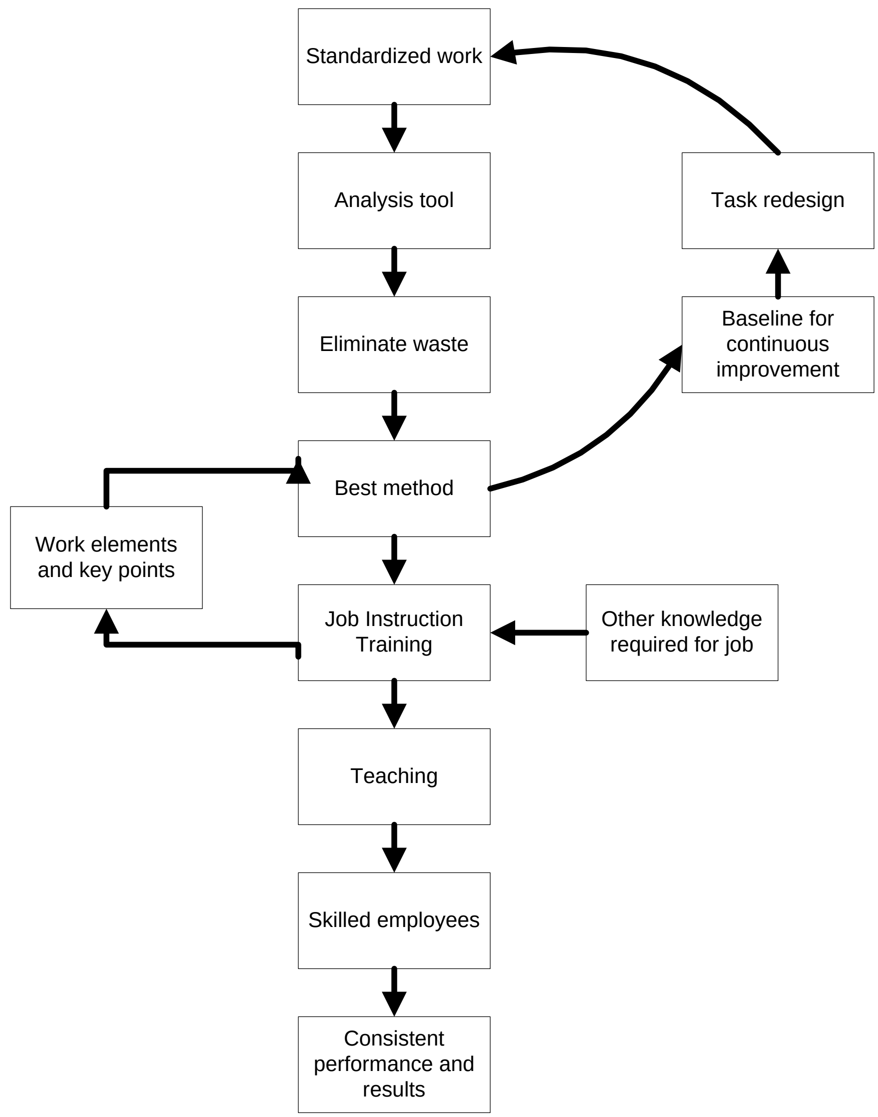



Figure 2-10 Relationship of Standardized Work to Job Instruction (Figure 6-1 in Liker and Meier 2007)

In understanding standard work, all processes have three types of tasks: (1) routine core, (2) nonroutine core, and (3) ancillary. Routine core tasks should be annotated on the job breakdown worksheet. Nonroutine core and ancillary tasks are necessary to support the overall work but can have multiple ways of completion (Liker and Meier 2007). Ancillary tasks are more random in nature and take place on an as-needed basis.

Standardizing work does not mean making all tasks highly repetitive; rather the intent is to define the best process and to reduce variation in the work process as much as possible (Liker and Meier 2007). Repeatability is not as important for nonroutine work as it is for routine work. Focusing on the entire system is a requirement to ensure that local optimization does not occur.

To avoid overanalyzing a system, tasks should be classified according to table 2-6.

| Percentage of steps in the work process | Importance | Effect on work |
|---|---|---|
| 15 - 20% | Critical - work must be highly consistent | Definite effect on results if performed out of range |
| 60% | Important - work must be consistent within a slightly wider range | Probable effect on results if performed out of range |
| 20% | Low importance - work method may be variable | Not likely to effect results regardless of method |

Table 2-6 Breakdown of Work Tasks by Importance (Table 7-3 in Liker and Meier 2007)

Critical work steps are by definition vital to the product and must be performed with a high level of quality and consistency. If the critical steps are not performed well, rework may occur. Liker and Meier (2007) say critical steps make up between 15 and 20% of the entire work. The bulk of work falls under important. Important work has a wider tolerance for acceptance but must maintain a high level of consistency to ensure the final product is not defective. Low important work can be accomplished in a variety of ways and will not affect the results of the final product. The key is to (1) identify the critical steps, (2) define a best standard method, and (3) then train all personnel to that method (Liker and Meier 2007). Management should focus on the critical steps and stress that the standard work procedures be followed. Lesser important tasks should operate within a larger defined range as long as the variation does not negatively affect the quality of the product.

Identifying key points to a process and reasons why they exist is a major step in developing standardized work procedures. The key points should be stated in positive "how to" language rather than in negative voice. Liker and Meier (2007) identify five types of key points exist (1) safety, (2) quality, (3) productivity, (4) special technique, and (5) cost control. Table 2-7 describes each category.

| Category | Description |
|---|---|
| Safety | Primarily related to injury avoidance or repetitive stress injuries |
| Quality | Provide specific instructions on how to perform a step without making mistakes that cause defects |
| Productivity | Techniques to ensure process is performed within the correct amount of time |
| Special technique | Aspects of a job that require special finesse |
| Cost control | Methods that are necessary to maintain the standard cost of products |

Table 2-7 Types of Key Points (modified from Liker and Meier 2007)

From my point of view, the construction industry lacks standard work. Too often in the construction industry, processes are recreated each time a new project starts. One reason for this is that the team that manages and constructs each project is different. Management teams are different and all personnel must determine how they will work with each other, creating an ad-hoc process to accomplish communication. Then, when the project is complete, and a new one starts up, a new process is created. This creates rework.

### 2.4.7 Computer Simulation of Lean Concepts

Lean techniques have been explored through several different simulations. Tommelein (1998) explored pull-driven scheduling by modeling materials management of pipe spools for process plant construction. She developed three models to illustrate the improvement that pull-driven scheduling can accomplish. The first model explores the process under no coordination, the second model explores the process through perfect coordination, and the third model utilizes real-time feedback to the fabricator so pipe spool delivery can be re-sequenced. By implementing pull-driven scheduling, buffers and inventory can be reduced while improving project timelines.

Modeling organizations with an ability to determine how organization was accomplished through the virtual design team (VDT). VDT is a multiple set of computer models that began in the early 1980's. This software extends Galbraith's (1977) qualitative concept of first order determinants impact on organizational success. The first order determinants are direct work, coordinated work, and institutional work. This research program views these three types of work as quantities of information to be processed by workers and managers in the organization. VDT analyzes how activity interdependencies raise coordination needs and how organization design and communication tools change team coordination capacity and project performance (Levitt 2002).

Halpin and Kueckmann (2002) explored lean construction through computer simulation. They describe the challenges to implementing lean construction techniques but offer simulation as a tool to accomplish a form of validation. They discuss the trend of making the product servant to the process because cost and quality improve. While in the construction industry, the process is servant to the product where the focus is on the end product and from there, the methods or processes to achieve the end state are generated (Halpin and Kueckmann 2002).

Deleris and Erhun (2005) used simulation to analyze risk management of a supply network for a Silicon Valley high-tech firm. The company questioned the adequacy of their supply network that was developed through partnerships and their geographical location. The goal of the research is to determine the robustness of the company's supply chain, not an optimal solution of the supply chain. They define robustness as the ability for the system to stabilize under a variety of disrupting events. A supply chain in this research is a set of sites connected through a network. This network is made up of suppliers, assembly/subassembly facilities or distribution centers. The simulation was used in two ways: (1) A loss evaluation tool for what-if scenarios for strategic discussion and (2) the basis for a risk assessment of the network based on Monte Carlo simulations.

To evaluate robustness of the supply network Deleris and Erhun evaluated four scenarios: (1) possibility of employee strikes, (2) shortage of components, (3) severe political instability in various regions, and (4) disruptions caused by hurricanes. The simulations were run using ad-hoc estimators for the likelihood of each of these scenarios. However, the research recommends a sensitivity analysis be conducted to understand the impact of each of the scenarios on the robustness of the company's supply network.

Agbulos et al. (2006) explored lean concepts and used computer simulation analysis to improve efficiency of drainage operations maintenance crews. They concentrated on six types of maintenance crews: (1) cleaning mains by low pressure flushing (LPF), (2) cleaning mains by high pressure flushing, (3) scheduled mechanical cleaning of catch basins (CBC), (4) inspecting mains by televising, (5) commercial establishment investigation, and (6) service-line rodding and televising. This research describes the application of an industrial engineering philosophy of work measurement, lean production theory, and simulation to capture current work methods, generate and test alternative methods, and develop new productivity standards for drainage maintenance operations crews (Agbulos et al 2006).

Each step of the work was determined using a work breakdown structure. They observed and recorded each the average time for each step. Agbulos et al. then labeled each step as value added or non-value added. They determined 63% of the processes were non-value added. They suggested two improvements: (1) eliminate initial surface inspection and (2) include parallel inspection of manholes during the flushing activity. The process was re-designed and a simulation model estimated 16% productivity improvement. When the re-designed process was applied to the real system a 10% increase in productivity was realized (Agbulos et al. 2006). This research reinforces that simulation can be used to predict improvements of a re-design process.

Yu et al. (2007) researched a hybrid approach that combines process flowcharting and simulation to analyze and improve production processes of prefabricators. They focused on factory-built structural components for house construction that large volume builder's use. Their research methodology includes seven steps: (1) Collect the information needed for process flowcharting, (2) create process flowcharts, in collaboration with the prefabrication plant manager, (3) gather operation data, (4) build a simulation model based on process flowchart and operation data analysis, (5) identify opportunities for process improvement, (6) create a new process flowchart depicting the improved processes, and (7) simulate the new processes to predict improved productivity

(Yu et al 2007). The research illustrates the use of computer simulation as an effective tool to plan process improvements.

The process to deliver factory-built structural components in their research is a make-to-order process. Structural components are fabricated only when site managers make a request for an item. In lean production, this technique is called pull, where an item is pulled into manufacturing by the downstream player. The use of pull reduces the amount of inventory that is required to be on hand but increases the lead time from order to delivery. The computer simulation showed a 6.5 day lead time from ordering to erection and was validated through observational data.

The utilization rate of the manufacturing facilities was calculated to be 35% and a value added ratio of 67%. Yu et al. (2007) determined that several factors were the cause of low utilization and value added ratio. These factors include absenteeism of key employees, low work efficiency, materials not available when needed, improper manufacturing schedule, low morale, no job design or clear definition for each work position and poor facility layout.

Yu et al. developed five process suggestions: (1) change the structure of the workforce, clarify the job definition and reorganize into self-managed teams, (2) train a specialized work force to increase efficiency, (3) change the process from make-to-order to make-to-schedule and establish a production schedule to allocate resources and develop a weekly work plan for each job assignment, (4) redesign the facility layout to reduce material movement, (5) build lasting partnerships with suppliers and share the benefits of just-in-time supply. These five suggestions are complementary to the philosophy of lean production, specifically suggestions 3, 4 and 5. It is imperative that production processes look to a weekly work plan to determine the reliable work planning. As mentioned in the pipe spool model by Tommelein (1998) seeking the use of standard products improves process efficiency which can also be applied to this situation.

Yu et al created three simulations using the following scenarios. (1) The house components are fabricated following the improved process. (2) Job time of each task, except transportation is improved by 20% due to management improvement suggestions. (3) The improved production process has operated for one year, and the job time of each task decreases following a standard learning curve outlined by Steward et al. (1995).

The results of the scenarios reduced the lead time to 6.5 days. The first scenario reduced the lead time to 5.0 days. The second scenario reduced the lead time to 3 days which matched the cost breakeven point for the production plant. Achieving this lead time reduction required worker productivity to increase 20%. The third scenario provided only a minor improvement over scenario two, because the facility design (scenario 1) and production method (scenario 2) provide the most improvement (Yu et al. 2007).

Schroer et al. (2007) evaluates several critical factors affecting manufacturing through simulation. They take a manufacturing line with six process cells and evaluate takt time, line balancing, kanban capacity, and vendor managed inventory (VMI).

To evaluate kanban, which is the amount of parts allowed to be at each work station, another set of simulations were conducted. It was found in this situation that increasing kanban resulted in diminishing returns because the process flow was matched. Therefore, if the process flow has little variation, increasing kanban does not improve system flow.

To evaluate vendor managed inventory, Schroer et al. (2007) evaluated a series of changes to the supply chain and made the following conclusions.

1. The reduction of all inventory is not feasible in situations with high levels of variability.
2. Production is sensitive to the Kanban size between stations.
3. Line balancing to takt time is critical to meet customer demand.
4. Location of fulfillment centers, along with reorder point and reorder quantity impact production.

Mao and Zhang (2008) defined normal and interactive activities instead of traditional value added and non-value added steps to develop a framework to reengineer processes. Computer simulation was implemented to explore the process changes. The framework was applied to studying tunneling operations. The research evaluated a current-state process and then proposed an alternate process that improved flow and introduced a different technique to remove material from the tunnel (Mao and Zhang 2008). They define a normal activity as serving only one workflow while an interactive activity serves more than one workflow. An interactive activity joins different workflows together and cannot occur until all of its requirements are met and can lead to the variability in a system.

Mao and Zhang (2008) established ten steps to their framework.

1. Develop work breakdown structure
2. Abstract project activities
3. Model construction process
4. Reduce supportive activities

5. Reduce interactive activities and minimize their interactions
6. Determine and modify critical workflows
7. Reduce activity duration
8. Reengineer construction process
9. Evaluate the reengineered construction process through computer simulation
10. Technologically evaluate the reengineered construction process

This framework revealed four improvements to the tunneling operation

1. The TBM excavation activity can be linked to the dirt removal activity improving the flow of the system
2. The survey activity is merged into the TBM excavation activity
3. Eliminate the vertical movement cycle because the continuous dirt removal system transports dirt from the face of the TBM continuously to the surface.
4. Reengineer a typical tunneling process that reduces liner installation duration.

The research presented in this section combines real world situations with computer simulation as a way to improve processes. This is what the research in this dissertation is trying to accomplish. It will take a baseline process, calibrate a model to fit data provided by the organization. Then I will make a change to the process and use simulation as a predictive management tool.

One major tool used in the design and construction of healthcare facilities is a computer technology that allows the building to be constructed in a virtual space. The next section provides further information on this modeling technology.

## 2.5 Building Information Modeling (BIM)

Building information modeling (BIM) is the process of generating and managing building data during its life cycle (Eastman et al. 2008). It allows design teams to construct an accurate virtual model of a building in a digital environment. This digital rendering of the project contains information that can be used for construction, fabrication, procurement and project management activities. BIM can also be used to understand the lifecycle of the facility and if used correctly, provide a higher quality project at a lower cost and shorter project duration. Eastman et al. (2008) consider BIM as a process of human interaction that involve broad process changes from an isolated design process to a collaborative design process and not just a tool to convey design drawings.

Currently the use of BIM as a communicative tool is centered on the design team. In California, the regulatory agency is not currently using BIM as a tool to expedite plan review, however, since BIM is widely used in the design and construction industry it is important to know the current state of this emerging technology.

### 2.5.1 Current Architecture, Engineering, and Construction (AEC) Environment

The current AEC industry is fragmented and depends on time consuming and unwieldy modes of communication such as email, fax, and paper-based design drawings. Errors and omissions involved with paper-based processes increase delays, costs, rework, and lawsuits, evidenced by the high cost to obtain errors and omissions insurance. New technologies such as 3D CAD have been under development over the past three decades. However, the advance in technology for information exchange is mired in inefficiency and has not mitigated the conflicts that arise from a paper-based document system (Eastman et al. 2008).

A common problem with a paper-based process is the time it takes to develop critical assessment information from the design documents such as cost estimates, energy analysis, architectural elements, structural details, etc. These analyses occur late in the design process resulting in the need to perform value engineering which in many instances detracts from the original design intent (Eastman et al. 2008). Value engineering is the process of finding cost savings in the design to reduce total project costs.

Maged, Abdelsayed, Tardif, Murray & Associates, a construction company located in Quebec, Canada collected the following data to illustrate the deficiencies in the current design and construction process (Hendrickson 2003):

- Number of participants (companies): 420 (including all suppliers and sub-sub-contractors)
- Number of participants (individuals): 850
- Number of different types of documents generated: 50
- Number of pages of documents: 56,000

Managing this amount of information and people is a difficult task and is amplified if the project is more complex such as in healthcare facility construction due to the other participants involved. A system that can simplify the different types of documents generated and the number of documents will certainly improve the design and construction process. I believe that the system that can accomplish this simplification is

BIM. Many types of computer software claiming to be BIM technology exist and it is important to understand what is not BIM technology.

### 2.5.2 What is Not BIM Technology

Many manufacturers boast about their BIM technology which causes confusion of what BIM technology is. Therefore it is important to describe what does not constitute BIM technology.

Models that contain 3D data only and do not have attributes assigned to objects within the drawings is not BIM technology. These models are purely used for graphical visualization and contain no intelligent tags of what objects are within the drawings. These types of drawings cannot support data integration and design analysis (Eastman et al. 2008)

Eastman et al. (2008) considers systems that support change behavior as BIM technology. Drawings that contain object information but cannot adjust their information when changed is not considered BIM technology. Without the ability to automatically adjust model information, during a change and to inform the design team of issues, an environment of inconsistent information will arise.

Eastman et al. (2008) do not consider it a BIM technology if the model simply builds upon multiple 2D CAD reference files to construct a 3D model of the project. This process does not guarantee the 3D model is feasible, consistent, and countable.

Eastman et al. (2008) do not consider it a BIM technology if the model can not update dimensions in one view and reflect the changes in all other views. This creates an environment where errors will propagate and misinformation will be disseminated to the design team.

### 2.5.3 Design Benefits of BIM

Eastman et al. (2008) describe seven design benefits of BIM technology.

1. Earlier and more accurate visualizations of a design - The 3D model generated by the BIM technology is not built up from 2D drawing views. The design from the start is constructed in a 3D manner allowing visualization of the design at any stage and the information presented will be dimensionally consistent in every view
2. Automatic low-level corrections when changes are made to design - The objects used in design are controlled by intelligent information to ensure proper alignment (e.g., map to grid). This reduces the user's need to manage the design changes.
3. Generate accurate and consistent 2D drawings at any stage of the design - 2D drawings that are accurate, consistent, and without errors can be extracted from the BIM technology at any time. This reduces the time to generate construction drawings for the design team. When changes are required, the drawings can be generated as soon as the design changes are implemented into the 3D model.
4. Earlier collaboration of multiple design disciplines - BIM technology enhances the ability for multiple design engineers to work on the model simultaneously. This ability reduces design errors and omissions. It also provides an avenue for earlier insight into potential design problems and allows for continuous improvement of the drawings. This is more efficient than applying value engineering to the design after the major design decisions have been made.

5. Easily check against the design intent - BIM technology provides 3D visualizations of the project earlier to accommodate space utilization, cost estimates, and material quantity take offs. In technical facilities such as healthcare facilities the design intent can be checked against code requirements. Space use of the facility can also be checked to ensure correct space allocation.
6. Extract cost estimates during the design stage - At any time during the design, BIM technology can extract accurate material quantities for cost estimates. In early stages of a design, a cost estimate is based on square footage. However, using BIM technology, costs of the facility can evolve rapidly and the cost impact of design decisions can be easily obtained before a specific design is detailed at the construction level. As a result, better decisions can be made regarding costs using BIM technology.
7. Improve energy efficiency and sustainability - Linking the model to energy information can provide an evaluation tool of the cost to operate the project. This is not possible with a 2D design. In a 2D design, the thought of energy use is typically performed at the end of the design stage. The ability to tie the 3D BIM technology to energy analysis tools makes it possible to build higher quality facilities that are also energy efficient.

### 2.5.4 Construction and Fabrication Benefits of BIM

Eastman et al. (2008) describe six construction and fabrication benefits of BIM technology.

1. Synchronize design and construction planning - The ability to tie the 3D model to the construction schedule provide insights into what the project will look like day to day. This ability to see day-to-day progression reveals sources of problems such as site access, crew safety, and space conflicts. Such pre-planning is not possible using 2D (bid) documents. The 3D model can be improved if temporary construction items are included such as shoring, scaffolding, cranes, major access avenues and these items can be linked into the construction schedule to appear at the appropriate time.
2. Discover design errors and omissions before construction - Because the 3D model is the source of all 2D drawings, the model can highlight design errors due to clashes. Since all the disciplines are involved with placing their systems into the model, the multi-system interfaces are easily checked. Timing of which system goes before another can also be revealed using BIM technology through the use of first run studies.
3. React quickly to design or site problems - The impact of a suggested design change during construction can easily be entered into the building model and the model will update instantly informing all players affected by the change. Project production is not disrupted because design changes are resolved quickly.
4. Use design model as basis for fabricated components - BIM technology can be used to provide fabrication level detail so additional drawings are not created. If the building information model contains this fine level of data, the information can be sent to a fabrication unit directly and the item can be made without delay, increasing project productivity.

5. Better implementation of lean construction techniques - Lean construction techniques require tight coordination between the owner, design team, general contractor and subcontractors to ensure work is performed when appropriate with available resources. BIM provides an accurate model of the design and required materials which provides the foundation for improved planning and scheduling. BIM technology can improve just-in-time delivery resulting in reduced inventories. This reduces the cost and allows for better job site collaboration.
6. Synchronize procurement with design and construction - An accurate list of materials makes it possible to work with suppliers on what is needed for the project. The quantities, specifications, and properties can be sent directly to the suppliers to avoid mishandling of information.

2.5.5 Post-Construction Benefits of BIM

Eastman et al. (2008) describe two-post construction benefits of BIM technology:

1. Better manage and operate facilities - The owner can be provided a building model that consolidates the information of all mechanical equipment, control systems, and other large facility purchases. The owner can use this information to ensure the facility is operating within the intended design requirements.
2. Integrate with facility operation and management systems - An updated building model at the end of construction provides a source of information about the as-built spaces and systems and can be used as a starting point for facility operation. The model can be integrated with facility system sensors to allow the facilities to be operated remotely.

### 2.5.6 Challenges of Implementing BIM

Eastman et al. (2008) describe four challenges to implementing BIM technology:

1. This new technology has not been adopted by every firm and a standardized platform has not been adopted. Therefore, getting design team members to use a specific BIM technology is challenging. If members of the design team use different modeling tools, then additional effort is required to transfer the models from one platform to another which can also lead to information errors.
2. Legal changes to documentation ownership and production are likely to occur because a legal debate arises, on who owns the multi-discipline, fabrication, analysis, and construction data information and who pays for them. Also, who is ultimately responsible for the accuracy of the building model? Facility owners are slowly resolving these issues because they see the benefit of using BIM technology and are contractually requiring the use of BIM technology on their projects. Professional groups such as AIA and AGC are developing guidelines and contract verbiage to cover issues arising from using BIM technology.
3. The use of BIM technology requires construction information to be used early on in the design process. This requires a change in current practice and organizations resist change. However, as BIM gets to be more widely used, information sharing will become easier, but sharing the building model is not a natural process for many design and construction firms.
4. Implementation issues arise when changing from a 2D to 3D environment. It isn't as easy as changing the software. To correctly implement BIM technology, the process

of information flow must be understood prior to adopting BIM technology. Firms have to decide which software to use, acquire the software, and train personnel, which is expensive.

BIM technology is certainly a technology that is here to stay and enables improvements to facility construction. However, more standardization and education of BIM technology implementation is required. One such construction player that needs education on BIM is regulatory agencies. These agencies are an intermediate user of the drawings produced using BIM. One such organization that is trying to understand where BIM fits into their review process is the Office of Statewide Health Planning and Development. The history and how the organization currently works is discussed in the next section.

## 2.6 Office of Statewide Health Planning and Development (OSHPD)

The Office of Statewide Health Planning and Development (OSHPD) is the focus of this dissertation research. Following is a brief discussion on OSHPD. The Sylmar earthquake of 1971 was a 6.6 magnitude earthquake that caused severe damage in four major healthcare facility campuses in California. Two healthcare facility buildings collapsed killing forty-seven people and three others were killed in another healthcare facility that nearly collapsed (Seismic Gov 2001). To ensure that facilities could withstand a seismic event, the State of California enacted the Alfred E. Alquist Hospital Seismic Safety Act in 1973.

In approving the Act, the Legislature noted:

“[H]ospitals, that house patients who have less than the capacity of normally healthy persons to protect themselves, and that must be reasonably capable of providing services to the public after a disaster, shall be designed and constructed to resist, insofar as practical, the forces generated by earthquakes, gravity and winds.” (Health and Safety Code Section 129680)

A major modification to the Hospital Seismic Safety Act occurred after the 1994 Northridge earthquake where 23 healthcare facilities had to suspend operations due to over $3B in damages (Calhealth 2008). In response to this seismic event, SB 1953 was passed requiring healthcare facilities to comply with three seismic safety deadlines:

1. 2002: major non-structural systems such as backup generators, exit lighting, etc. must be braced
2. 2013: all general acute-care inpatient buildings at risk of collapsing during a strong earthquake must be rebuilt, retrofitted, or closed; and
3. 2030: all healthcare facility buildings in the state must be operational following a major earthquake.

2,700 general acute-care inpatient healthcare facility buildings are required to meet the mandates of SB 1953 with an estimate construction cost of $24B. In addition, a study shows that 66% or two out of every three healthcare facilities are losing money from operations. Additional data shows that approximately one third of the state’s urban healthcare facilities and more than half of rural and inner-city healthcare facilities are losing money from all sources of income (Calhealth 2008). Healthcare facility owners facing tighter budgets require new or renovated hospitals to come into service as quick as possible to start the revenue stream. This puts strains on the design, permitting, and construction which is a major reason for this research. Improving the permitting process as shown later in this dissertation can improve the economic programs and ultimately improve healthcare across the State of California.

The Office of Statewide Health Planning and Development (OSHPD) is charged to oversee the implementation of SB 1953, more specifically, the Facilities Development Division which is further explained in the next section.

### 2.6.1 Facilities Development Division (FDD)

The Facilities Development Division (FDD) of the Office of Statewide Health Planning and Development is responsible for the permitting of all healthcare facility construction in California, both new construction and renovation. This agency ensures healthcare facilities meet a certain level of seismic performance, in order to ensure they remain functional during and immediately following a major catastrophe (specifically an earthquake). Obtaining drawing approval for new construction or renovation of a healthcare facility can take up to two years, which is detrimental to a healthcare facility owner's business plans. A common scenario is that owners want to fast-track their projects, i.e., start construction early while parts of the design remain to be checked for quality. The FDD continues to review the project; however, if information is missing or errors are evident, the FDD returns the drawings to the design team for correction. This is known as a "back-check." Back-checks add time to final permitting and cause variation in the flow of information. This scenario is riddled with rework cycles. These projects are reviewed by seven different sections of the FDD.

The staffing of each geographic region depends on the workload they have historical experienced. The coastal region due to population density has more healthcare facilities and reviews the most drawings while the south and north regions review fewer drawings. The FDD consists of 235 personnel and is divided into seven different geographic regions.

### 2.6.2 Stakeholders in California Healthcare Facility Construction

In addition to healthcare facility project team members and OSHPD, many other government and industry agencies are involved with construction of a healthcare facility in California (Figure 2-11). Industry project participants include the contractor and sub-trades and the owner and owner representatives. Government oversight of healthcare facility construction is accomplished not only by OSHPD but also by local government, Department of Health Services, and the Department of Geologic Services.

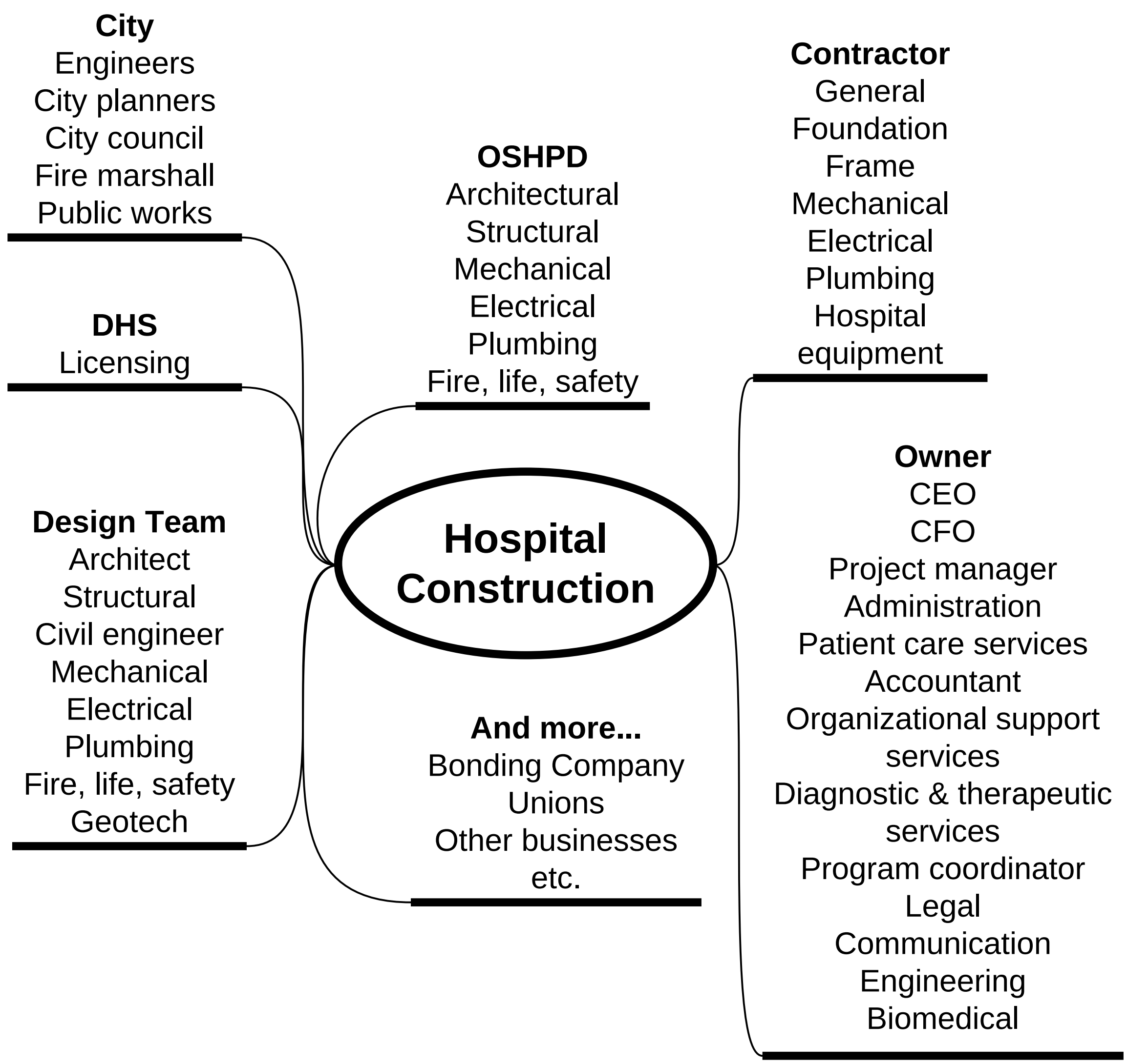



Figure 2-11 Stakeholders Involved with Healthcare Facility Construction in California

### 2.6.3 Project Production Systems Laboratory (P2SL) Healthcare Improvement Initiative

Starting in October 2006, P2SL commenced an initiative to improve healthcare facility permitting in the state of California. This initiative included healthcare facility owners, architects, engineers, contractors and OSHPD. During the first five meetings, teams developed a current state map of how four major healthcare facility owners delivered projects to OSHPD for review.

The vision for this initiative was to (P2SL 2007):

1. Reduce the waste in design, permitting, and construction of acute care facilities.
2. Reduce costs associated with the current facility delivery process, and increase the value of facilities.
3. Level the workflow of the entire project delivery team and create an environment that keeps people involved in value added work.
4. Accelerate the overall delivery process by reducing risk associated with unpredictable variability.

Realizing the need to improve the delivery of healthcare facilities, Senate Bill 306 was enacted in January 2008 allowing owners and design teams to enter into a phased review process with the FDD. OSHPD "in its sole discretion, may enter into a written agreement with the healthcare facility governing authority for the phased submittal and approval of plans." First, we must understand the current process healthcare facility drawings are reviewed and permitted in California.

### 2.6.4 California Healthcare Facility Permitting Processes

The permitting process primarily involves the design team submitting their design drawings to a regulatory agency. The regulatory agency then reviews, makes comments, and finally approves the design drawings for construction. In California, the permitting process is very similar.

Healthcare facility design drawings are reviewed in three ways. The first is the traditional '100% contract drawings' where the design team completes the entire design package (which on a large project could be thousands of drawings) and then delivers it to

OSHPD/FDD for review. FDD plan reviewers comment on non-compliance issues and then send the set back for correction by the design team. This cycle continues many times until the drawings are deemed code compliant, whereupon FDD approves them. If the drawings fully comply with the California building code from the start of review, this is the most efficient way for the drawings to be permitted through the agency. However, this situation rarely occurs.

The second and most often used way to review and approve drawings is to break the project down into phases. A 'phased project' divides the project into major systems, to include underlying utilities, foundation, structure, mechanical systems, and roof systems. This way differs from the '100% contract drawings' in that the design team can submit each phase as soon as it is complete. This process decreases the batch size of the design drawing submittals but it increases the number of project reviews FDD has to perform.

The third way is to request 'partial permits.' This differs from the phased approach in that each phase separately can be approved and permitted to construct. The upside is this approach allows the construction process to begin earlier by reducing batch sizes, but it also increases the number of reviews. The downside is the difficulty of determining which parts of the drawings are approved with permits and which are not. An example of this is: Where do underground utilities start and stop in relation to the foundation?

The current batch process of healthcare facility permitting does not create an environment where errors are easily detected, analyzed, and corrected. In fact, this system works against the culture of working together to detect errors because many designers make their systems work, and hopefully the plan checkers do not catch any minor errors. Minor errors are easily missed because of the very large number of drawing sheets included in a healthcare facility design; something in excess of 3,000 sheets for a healthcare facility construction project. All of these processes create substantial rework, pushing back construction schedules and leading to significant cost escalation (e.g., Morris (2007) estimates escalation at about 12% per year). In addition, the FDD has a large amount of work resulting in a backlog of reviews, causing delays affecting business plans of large healthcare facility providers.

I believe that implementing a different way of designing and reviewing healthcare facility drawings can improve the time to receive drawing approval. This research uses Lean production theory, to establish an alternative way of permitting healthcare facility designs. Many issues arise with the FDD review process because members within industry do not understand the process of how healthcare facility drawings are approved. During the design process, the development of a healthcare facility proceeds through the business case/feasibility study, programming, schematic design, design development, construction documents, and permitting. This process can take upwards of two years to complete which severely alters healthcare facility business plans and must be considered prior to constructing a new healthcare facility. The plan review process can involve as many as ten different organizations from the owner, architect, designers and the subcontractors (civil, electrical, mechanical), general contractor, FDD and other government agencies.

# 3. TAXONOMY OF REWORK

## 3.1 Section Abstract

Based on the premise that healthcare facility design and construction costs are escalating due to rework in upfront (1) planning, (2) programming, (3) design, and (4) permitting phases a study to understand where waste occurs performed by a group of healthcare facility owners, architects, designers, contractors and state permitting personnel. This study identified 158 process waste items. Chapter 4 categorizes these 158 waste items using an existing taxonomy of rework and extending it as needed. An existing taxonomy of rework contains five categories: (1) human resource capability, (2) leadership and communication, (3) engineering and reviews, (4) construction, planning, and scheduling, and (5) material and equipment supply. The extension includes three new categories: (1) planning, programming, and budgeting, (2) design planning and scheduling, and (3) design review.

Chapter 3 identifies what causes of rework are within the California healthcare facility design and permitting phases. Understanding these waste items provides a foundation on which to build new practices that avoid costly design and permitting delays. The proposed categories were presented to industry members in two workshop presentations to validate the three category extensions.

## 3.2 Background and Scope

As mentioned in section 2.6, the work in this chapter builds on the process centered on OSHPD. To understand the delivery of healthcare facilities in California, it is important to capture the current state of operations. Four hospital owners were present at the initiative. After mapping their current process it was determined that each owner had a different way of delivering healthcare facilities in California. These process maps were consolidated and waste items were identified and documented. The consolidated map and waste items serve as the basis for the work presented in this section.

## 3.3 Methodology and Methods

Qualitative research explored the causes of rework within the state of California healthcare facility design, permitting, and construction industry. A cause and effect diagram categorizes the causes of rework under Fayek et al. (2004) original five headings and three additional headings. Data was sampled from a series of workshops that developed current and future state maps. The identified waste items were screened for duplication and placed into a two-tiered categorization system.

## 3.4 Data Collection and Rework Classification

Kauro Ishikawa (1982) developed the “fishbone” diagram or cause and effect diagram as a qualitative tool to present cause and effect relationships. In developing process improvements, quantitative tools (such as multiple regression, analysis of variance, and multi-variate charts) can be used to analyze cause and effect relationships. However, use of quantitative tools should be preceded by qualitative analysis to ensure existing knowledge is acquired and quantitative tools are focused in the right direction (Schippers 1999).

Rework has many sources in the construction industry. Figure 3-1 shows a cause and effect diagram documenting the causes of rework in a facility project. To the right of the dashed line, it shows five categories of rework: (1) human resource capability, (2) leadership and communication, (3) engineering and reviews, (4) construction planning and scheduling, and (5) material and equipment supply.

This taxonomy of rework (figure 3-1) shows two levels of categories, the first level represents the five main branch headings and the second level the horizontal arrows from each branch of the cause and effect diagram. Fayek et al. (2004) further described the secondary level by a third level of detail (not shown). Their extensive work in the causes of rework lacks causes tied to the design and permitting phases of a project.

Following are my interpretations of the five categories proposed by Fayek et al (2004).

A. *Human Resource and Capability* focuses on the physical work that is conducted to complete the construction project. It includes the direct supervision of field work.

B. *Leadership and Communication* focuses on the project management team and subsequent communications amongst the team members. It also includes end user buy in, however, it does not include the programming and budgeting process that owners participate in.

C. *Engineering and Reviews* focuses on the process that occurs between design engineers and how scope changes cause rework. It does not include the interaction that the design engineers have with regulatory agencies.

D. *Construction Planning and Scheduling* focuses on the execution of field work where designs are implemented. It does not include rework that occurs within the design phase of the project.

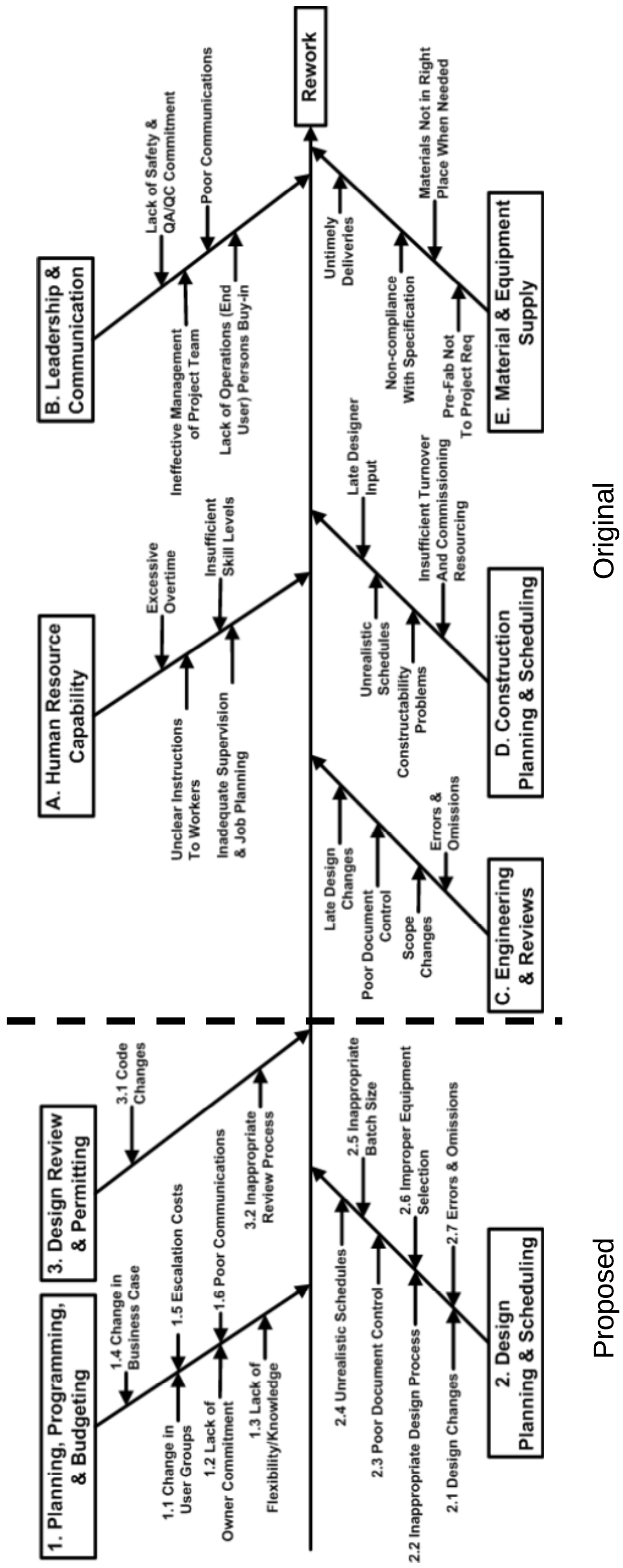



Figure 3-1 Rework Cause and Effect Diagram

E. *Material and Equipment Supply* focuses on the physical items that are utilized in the construction effort.

## 3.5 Categorization of Rework in Delivery of California Healthcare Facilities

The research presented here proposes three main categories be added to the existing taxonomy as presented by Fayek et al (2004). Figure 3-1 shows a consolidated cause and effect diagram, integrating my proposed three categories with Fayek's original five. It shows the three proposed categories to the left of the original five because the design and permitting phases occur prior to construction.

1. *Planning, Programming, and Budgeting* (PP&B) focuses on upfront actions including plan validation, a process where major stakeholders verify project budgets, timelines, scope, design, and labor and material costs. This category captures the causes of rework as it pertains to the owner's involvement with the project. This category has six second-level categories.

   1.1 *Change in User Groups* causes rework because the design team may have to change the facility layout and functions to accommodate new representatives of the staff. For example, a healthcare facility is trying to persuade a specific doctor to join their staff and promised to provide what he/she wants in a functional space. This leads to late changes in the design and multiple rework iterations because of the long lead time to delivery a facility while staffing occurs in a short lead time.

   1.2 *Lack of Owner Commitment* causes rework because the design team does not have clear direction of what user requirements will be. For example, rework may occur because an owner will ask the design team to explore multiple options and then not commit to a specific design because the owner has not committed to a single vision of the facility.

1.3 *Lack of Flexibility and Knowledge* causes rework because the owner will not make concessions on different design options that could support a particular requirement. The design team then makes changes to the design to accommodate owner requirements. For example, an owner initially requests a specific type of medical equipment for a surgical room. The design team accommodates this piece of equipment into the contract drawings. Then, as the facility is in construction, the owner requires a new type of medical equipment and is not flexible in using the original piece of equipment. This issue results in the cycle of technological innovation versus the time it takes to deliver a facility. As the project is being designed and constructed, new medical technology gets developed. Therefore, owners, wanting to provide state-of-the-art medical care will want to decide relatively late in the project to obtain the latest technology, however, this new equipment may require different design requirements resulting in rework. This situation is not unique to healthcare facility construction; Gil et al. (2004) researched this phenomenon in the semiconductor industry. He advocates a judicious postponement of design commitments to reduce waste and increase the reliability of the development process. Design teams can adopt a wider range of initial design criteria, that accommodates potential technological innovation to prevent downstream rework. However, if not managed properly, an increase in construction rework is likely.

1.4 *Change in Business Case* occurs when an owner revises the business plan which changes the services that the healthcare facility will provide, in response to market forces. For example an owner may change areas to support an additional surgical ward because a nearby hospital closes.

1.5 *Escalation Costs* cause rework. For example, when an owner does not adequately plan for cost escalation, as the project progresses, changes to design have to occur because the current budget cannot support the future facility and the revised business plan.

1.6 *Poor Communication* causes rework. For example, when the needs of the owner are not conveyed to the design team, the design team then has to make assumptions in order to proceed, likely resulting in rework later when owner needs are revealed.

2. *Design Planning and Scheduling* (DP&S) focuses on the design team and how they process information to complete the facility design. This category captures the rework associated with the design team, and any additional players such as contractors and specialty contractors. This category has seven subcategories.

2.1 *Design Changes* cause rework because the discipline engineers have to rework their designs to accommodate them. These design changes do not include owner driven changes which are a focus of another category.

2.2 An *Inappropriate Design Process* causes rework when information is not properly obtained by discipline engineers. For example, in mechanical design, a pressure exists to submit design drawings before they are completed for two reasons (1) to obtain regulatory agency approval and (2) to allow the sheetrock contractor to provide an estimate for their work. Regulatory agency approval is required before a construction permit is granted. Delays in obtaining this permit ultimately delays project completion. The sheetrock estimate is provided to the general contractor and owner to determine the project budget. Then, as the mechanical design is finalized, the completed design can differ from what was shown in previous design iterations which in turn will require another regulatory agency review and rework of the sheetrock estimate.

2.3 *Poor Document Control* causes rework because discipline engineers are not working off the latest set of design assumptions and criteria. For example, in foundation design, a geotechnical report can provide many seismic loading scenarios. Rework occurs when the structural engineer does not have the latest loading scenarios to design the foundation.

2.4 *Unrealistic Schedule* is likely to occur when the design team and other project members do not complete a well thought-out reverse phase schedule. A reverse phase schedule works backward from required intermediate and schedule completion dates. All project members participate in understanding how long each of their design and construction requirements will take. This information is then posted for all to see and information handoffs are clarified and agreed upon. A final schedule is then developed by all project members. A poorly planned reverse phase schedule results in poorly defined handoffs of information between design engineers; which causes rework.

2.5 *Inappropriate Batch Size* refers to the number of drawings that are transferred between discipline engineers or a regulatory agency. For example, a regulatory agency will review any and all drawings that are submitted, so if the design team submits a large batch of drawings that have incomplete information, they may receive comments that require extensive rework. Therefore, if the designers have a smaller set of drawings that are more accurate and complete, only those drawings should be submitted for agency review, rather than, submitting a large number of drawings that contain errors or lack of information.

2.6 *Improper Equipment Selection* is a cause of rework because medical equipment may require specific design requirements. For example, if the design team or owner selects improper equipment that does not meet user requirements, the discipline engineers will have to rework the design to accommodate the correct type of equipment.

2.7 *Errors and Omissions* cause a cascade of errors in the design leading to rework. For example, an incorrect column size is placed in the design. This error is used to calculate the required eight-foot corridor width in a healthcare facility. Later on in the design, it is discovered that a larger column size will be required resulting in less clearance in a healthcare facility corridor. Since healthcare facility corridors must be at least eight feet wide with no exceptions, if the requirement cannot be met due to the larger column size, then the entire floor space may have to be redesigned.

3. *Design Review* focuses on rework that occurs within a regulatory agency. This category has two subcategories.

3.1 *Code Changes* cause rework in many situations. Design code changes frequently as new testing and techniques are discovered to provide better quality facilities.

For example, a code change may force a structural design change when a new geotechnical analysis is developed that is technologically advanced to calculate seismic loadings. The national geotechnical code requires a geotechnical report for a healthcare facility use the latest analysis techniques. However, the state review code will not adopt the new geotechnical analysis until 2012. This situation causes confusion which leads to the design team not knowing which code to use and ultimately having to conduct rework to analyze the structure using the correct code requirements.

3.2 An *Inappropriate Review Process* causes rework. For example, the fire, life, and safety reviewer requires the design team to provide explicit information on the door hardware, when designers are not yet ready to provide it. If the design team provides that information to accommodate the plan reviewer and the door hardware has to be changed, rework for the design team and the plan reviewer will occur.

## 3.6 Limitations

Following are the limitations of this research.

1. This section does not contain all possible causes of rework, these rework causes capture the ones identified by the industry group, there could be more causes of rework present in the California healthcare facility construction industry.
2. This data is qualitative; it does not have quantitative information showing the overall impact of the causes of rework. This research does not attempt to show cost impact of

the causes of rework. This could be put into future work to determine the financial impact of each of these categories.

3. This research does not attempt to determine the quantitative impact due to the causes of rework. This includes the time impact to the project design and construction schedule.

## 3.7 Analysis and Results

I categorized the 158 waste items and developed figure 3-2 to show the relative contributions of each of the rework categories. For example, planning, programming, and budgeting resulted in 28% (42 items) of the 158 waste items.

Figure 3-2 shows six categories, three from the original taxonomy framework and the three extension categories. The two original categories of (1) human resource capability and (2) engineering and reviews were not necessary in categorizing the causes of rework in California healthcare facility design and permitting because no occurrences met those category descriptions. The three original taxonomy categories used in this research are (1) construction, planning, and scheduling <1%, (2) material and equipment supply 3%, and (3) leadership and communication 1%.

Figure 3-2 shows the largest contributors of rework in the design and permitting phase of a project are (1) *Design Planning and Scheduling* 51%, (2) *Planning, Programming, and Budgeting* 28%, and (3) *Design Review* 17%. This figure reinforces industry comments in regards to rework, "we do it to ourselves," because much of the rework is in the control of the design team. Controlling the *Planning, Programming, and Budgeting* aspects of facility construction are directly attributable to facility owners, yet a need or want for flexible programs always exists. I do not propose that business case programs be inflexible, in fact, I support flexible programs that will ensure state of the art healthcare services, nevertheless, owners must understand there can be a price for program flexibility such as increases in rework, project cost, and project delay. However, the impact of program flexibility may be reduced if proper set-based design techniques or delayed commitments strategies are applied. *Design Planning and Scheduling* is responsible for 51% of the causes of rework. The design process contains many areas where waste can be eliminated.

*Design Review* makes up 17% of the rework causes. An effort by a state regulatory agency to improve the review process that will remove causes of rework from all three proposed categories is currently underway. However, improving *Design Planning and Scheduling* may have the greatest effect in reducing rework in the process of permitting healthcare facilities. Improving can occur if owners take the time to properly plan, program, and budget for their facilities, (which will reduce the time to permit).

## 3.8 Relative Contribution Analysis

The relative contribution analysis mirrors the process, analysis and results conducted by Fayek et al. (2004). The analysis is based on the contribution of each rework cause to the overall number of rework occurrences (158). The sum of all rework percentages is equal to 100%. Figure 3-2 shows the percentages of the second level causes that contribute to the first level cause of rework. For example in figure 3-2, *Planning, Programming, and Budgeting* (PPB) contributes 28% to the total rework causes. We attributed 10% of the

28%, to *Lack of Owner Commitment*, 4% to *Owner Changes*, 4% to *Change in Business Case*, and 4% to *Change in User Groups*. A *Lack of Owner Commitment* occurs when the design team is waiting for owner decisions and approvals. Healthcare facility owners want to provide the best, most appropriate healthcare facility and may require additional effort in making final design decisions; however, this delay can impact project design. For example, conflicts between multiple owners on space use decisions can cause rework. This conflict may arise, for example, from an unresolved business program, poor project definition, and lack of commitment to facility scope.

*Design Review* resulted in 17% of the rework causes, 13% is due to *Inappropriate Review Processes,* and 4% to *Code Changes*. Some examples of *Inappropriate Review Processes* are incomplete reviews, inappropriate coordination of review, lack of documentation and agreements on code interpretation, and reviewer preference of solutions.

An inappropriate review process also includes lack of consistency in review staff, interpretation of code by field staff, and gaps between reviews (loss of knowledge or familiarity). *Design Planning and Scheduling* resulted in the majority of rework causes at 51%. Of this 51%, 34% is due to *Inappropriate Design Processes*, 6% to *Poor Document Control* and 4% to *Inappropriate Review Processes* of drawings prior to regulatory agency submission.

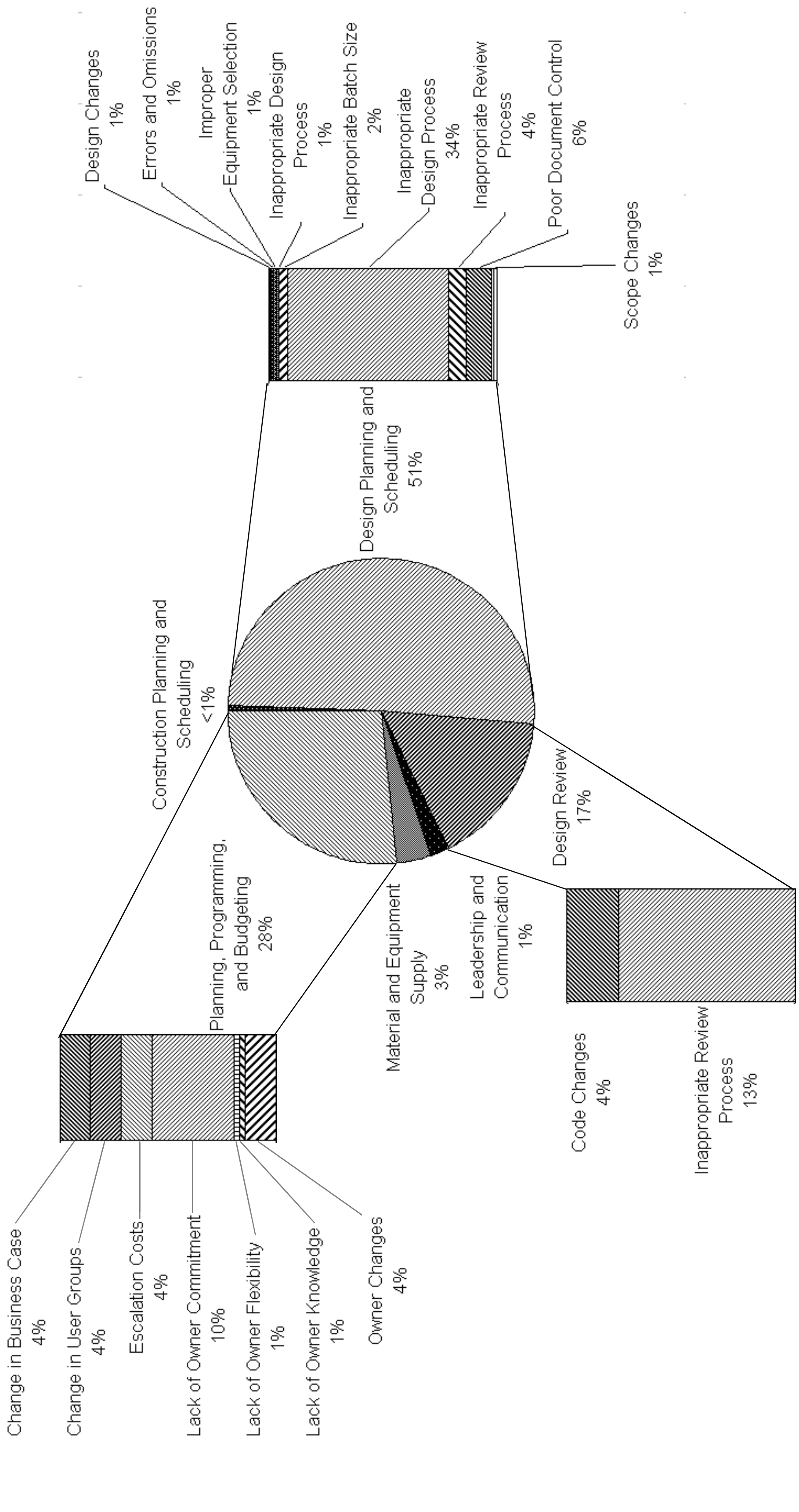

Design Planning and Scheduling 51%
Construction Planning and Scheduling <1%
Planning, Programming, and Budgeting 28%
Material and Equipment Supply 3%
Leadership and Communication 1%
Design Review 17%
Design Changes 1%
Errors and Omissions 1%
Improper Equipment Selection 1%
Inappropriate Design Process 1%
Inappropriate Batch Size 2%
Inappropriate Design Process 34%
Inappropriate Review Process 4%
Poor Document Control 6%
Scope Changes 1%
Change in Business Case 4%
Change in User Groups 4%
Escalation Costs 4%
Lack of Owner Commitment 10%
Lack of Owner Flexibility 1%
Lack of Owner Knowledge 1%
Owner Changes 4%
Code Changes 4%
Inappropriate Review Process 13%

Figure 3-2 Relative Contribution of Rework

An *Inappropriate Design Process* includes incomplete designs, e.g., where drawings are not complete due to a lack of coordination between design team members. It also includes exploring design options outside of project scope and failing to identify alternative methods of compliance. An alternative method of compliance is where the design team feels they can meet a code requirement using a different method from a prescribed standard design solution, however, the approval process for an alternative method of compliance can take up to one year. In California, depending on the situation, an alternative method of compliance can require additional regulatory agencies to review the proposed design solution for code adequacy. These additional regulatory reviews add time to the design and permitting process. However, during this regulatory review time, the design team continues to design the facility. If the alternative method of compliance is determined inadequate, the design team must find another design solution. Therefore, failing to identify alternative methods of compliance early in the design and permitting process is a major cause of rework. Other causes falling under an *Inappropriate Design Process* are improper timing of equipment selections, undefined information needed by team members, and incorrect drawings provided for a desired purpose.

## 3.9 Section Acknowledgments

Thanks to all that have and are participating in the California Healthcare facility Initiative. This research could not occur without the help of all P2SL member companies.

# 4. CASE STUDY I: WORKFLOW OF A MECHANICAL CONTRACTOR

## 4.1 Section Abstract

Design and construction changes often cause rework, increase a project's cost, and delay its delivery. I obtained data from a mechanical contractor in order to study rework timing and how it disrupts their detailing, fabrication, and installation processes. A set of simulation models illustrate the impact of rework timing. The focus is on early changes, that is, changes that become known when the contractor is detailing, so they can be dealt with either (1) right away during detailing, (2) during fabrication, or (3) during on-site installation. One model shows that dealing with changes in the detailing phase not only affects that phase but can have negative impacts on installation as well. Another model shows that detailing a project to a set of approved drawings and maintaining those until project completion, forces changes to be pushed downstream to site installation, which makes the impact of those changes more transparent to all players involved and can reduce negative iteration.

The question addressed in this chapter is: When early changes occur, is there benefit to incorporating them during site installation instead of trying to capture, re-detail, and change drawings? Practitioners can use this research to assess resources to avoid rework.

## 4.2 Background and Scope

This chapter focuses on how a mechanical contractor deals with changes in construction of a healthcare facility that requires a state-agency building permit. These concepts of changes timing, last responsible moment, not getting credit for correcting errors that do not occur, and the 90% syndrome contribute to making project management of such facilities complex. To deal with this complexity the mechanical contractor implements the last responsible moment to detail changes. This last responsible moment is when the change is needed in site installation. Once the site installers are ready to implement the agreed upon change is when the upstream process of detailing and fabrication occurs. This reduces the amount of delay between processes and makes the cost of change more explicit.

Changes in a construction project not only cause rework but they also can lead to significant cost overruns and schedule delays. Changes stem from owner-modified project requirements, design errors, omissions, etc. (Love and Li 2000). Research has shown that if changes are identified and handled as early as possible, it will pay dividends in future work (Ibbs 2005). This idea also is grounded in lean production theory (i.e., it is akin to stopping the assembly line as soon as a quality defect has been detected, and fixing it right there and then). Change in design is known to be less costly than change in construction, however, change in design might be needed several times particularly when the corresponding costs are perceived to be minimal. Because certain changes and especially those in the course of construction tend to be costly, some owners prefer to not invoke them but instead complete their project as planned and immediately thereafter initiate a ‘tenant improvement’ project to handle the previously-identified changes.

In the case studied here, a mechanical contractor (a subcontractor to a general contractor) decided to allow changes to design drawings to be pushed down the line and dealt with during site installation instead of dealing with them in the detailing phase.

"We do it to ourselves by detailing too early … I can see when a project will require rework when we detail without complete information … We end up chasing our own tail trying to catch the numerous changes that occur (Mohar 2008)."

On one project, this contractor tried to catch all of the changes to drawings as soon as possible and determine the effect of those changes prior to fabrication and site installation of materials. However, they had to work hard to track down where the drawings were and what items were in fabrication vs. what items had been sent to the site for installation. In addition, they had to put in extra effort to ensure that the site installers had the most up-to-date drawings to work from.

"It is extremely difficult to get drawings out of the field once they are sent out because the field personnel make a lot of notes on them. I have to physically go to each of the sites and pull them out of the trailers (Heier 2008)."

This caused communication errors to occur and, ultimately, some incorrect items did get installed so that some site rework had to be accomplished anyway. This case study discusses how early vs. late handling of changes can be modelled and reveals benefits of dealing with changes at the site. The benefits are (1) ease of more explicit accounting for costs incurred due to changes and (2) less negative iteration in the process.

## 4.3 Methodology and Methods

Purposeful sampling of the case study was used to select the mechanical subcontractor. This mechanical contractor is an expert in both dry side and wet side heating, ventilation and air conditioning installations and an expert in healthcare facility construction in California. In depth interviews were then used to collect information on their internal process from which a flow diagram is created. Data is obtained from the organization that was then used to construct a discrete event simulation model. The model was validated through an in depth interview with key members of the organization.

## 4.4 Types of Contracts

Different types of contracts are used to legally bind members together in producing a construction project. Following is a synopsis of the types of contracts, the role of the contractor, owner, designer and subcontractor in each contract type, their advantages, disadvantages and parallels to other industries. One statement can be made for every contract which is "few things are absolute, and almost always there are exceptions (Collier 2001)."

The first type is the firm fixed price contract also known as lump-sum and stipulated sum contracts. It has been the most common type of contract over the past 100 years however; today many of the larger construction contracts are not firm fixed price (Collier 2001). The concept of this contract type is to provide a complete and useable facility for a fixed price. This type of contract worked fairly well in dealing with a simple, complicated project, for example a small house. The contract along with the reputation of the builder and subcontractors and the availability of materials pretty much ensured that the owner would receive a house that was suitable and ready for occupancy. The house would be of a certain quality with all of the additional items of finishes, fixtures, fittings, and services despite it being clearly written in the contract. This concept of a lump-sum contract still exists today which requires the contractor to provide and install work that "is reasonably inferable from them (the contract documents) as being necessary to produce the intended results." The wording provides for many different interpretations, but it is the interpretations by the courts which bind the contractor. However, one main interpretation exists from the firm fixed price contract. A contractor is required to provide completed work for the general purpose for which it is designed and intended. For example, if a bathroom was located on the drawings on the second floor of a building but no design was done for the mechanical, electrical or plumbing, the contractor would still be responsible for installing those required materials to make that work function.

An owner's two primary tasks in any type of construction contract are:

1. Provide information and access to the construction site.
2. Pay the contractor according to the agreement and conditions of the contract.

The owner has very few primary tasks in a construction contract because most of the duties are passed to the architect and design engineers. The owner has more rights than tasks in a contract that include the ability to stop work if deficient work is being done or the contractor fails to provide adequate materials to the project. In addition, if this occurs, the owner has the ability to get the changes made at the cost of the contractor. In that same line, the owner has the right to terminate the construction contract if the contractor continually fails to meet the requirements of general conditions. However, the owner must get approval of just cause from the engineers. This shows the interrelatedness that the owner, architect, designers and contractors have with each other. The owner also has the right to accept defective or deficient work in most cases. However, in healthcare facility construction, this is not the case, an owner and contractor must abide by the building codes established by the state regulatory agency. Finally, an owner can establish a liquidated damages clause that penalizes the contractor if they fail to deliver the project on the requested timeline.

The architect or engineer has the primary role of being the owner's agent representative and is mostly involved with payment issues during the construction phase. Also, the architect or engineer acts as an arbiter between the owner and the contractor. In the design phase, typically the architects and design engineers are reimbursed as a percentage of the total construction project. In addition, the architect and engineers are responsible for clarifying information that is requested by either the owner or contractor during construction. This is called a request for information (RFI) and must be answered by the architect or design engineers. The architect or engineer is able to make a minor change within the construction phase without it affecting the lump sum cost or delivery of the project. However, if the work is above and beyond what is reasonably expected a change order can be processed for cost and schedule impacts. The designer and contractor have a joint responsibility to ensure that the work is constructed in the proper way which can become a source of dispute. These disputes are primarily based on whose responsibility it was that caused the error of work to occur. Other responsibilities of the architect or engineer are to provide certification of substantial work and also to issue the final certificate of payment.

The subcontractor has no obligations in a primary contract between the owner and the contractor because they are not a party to the primary contract. However, the contract between the contractor and subcontractor are typically lump sum contracts. The subcontractor's obligations are linked to the primary contract in which the contractor must ensure the work provided conforms to the contract drawings. Basically the subcontract and its obligations must mirror the primary contract to the extent appropriate to the work provided by the subcontractor. However, in many instances the subcontractor never reads or knows what is in the primary contract.

The supplier also has no obligation in the primary contract between the owner and the contractor. A supplier is much like the subcontractor in that they are an integral piece to the project and are affected by the primary contract. In the past, the supplier is farther removed than the subcontractor, but this is changing. In many instances the distinction between supplier and subcontractor is fading, with many construction products being prefabricated by the supplier prior to delivery to the construction project. Therefore, new contracts should recognize that this situation occurs and that suppliers may be redefined as specialty subcontractors who supply materials or components worked to a special design (Collier 2001).

The primary advantage of a lump sum contract to the owner is that he/she can examine all of the bids received and select the contractor that can deliver the work within their prescribed budget (if the design team has done their job). If the designer has done a good job in developing the contract drawings and writing specifications and the owner can resist making changes, it is possible to perform a firm-fixed price contract for the advertised price. However, this is hardly the case and changes can severely hurt the economics to the owner because the additional work has to be paid to the contractor based on a negotiated agreement. It is generally accepted that changes are a source of profit for the subcontractor rather than a loss (Berends and Dhillon 2004). The main disadvantage with the lump-sum contract is that complete design information must be developed prior to receiving bids from the contractors. This can significantly increase the time until construction start which has cost escalation impacts. Also, for bidders to make adequate estimates, all of the prescribed work must be detailed in the contract drawings. Any required changes during the construction phase will trigger a change order that will increase the total construction costs. Even the most dedicated and experience architects and engineers realize that not all of the design information can be known ahead of construction, but once the detail is drawn and specifications written, they become part of the entire primary contract and changes will result in cost impact to the owner. These cost impacts can threaten the project if they become too large for the owner to handle. Another disadvantage is the owner is deprived access to the expertise that the contractor possesses on how to build projects. They are not consulted during the design phase and do not have time or the inclination to provide design suggestions when the bid is put together. The contractor's main concern is production of work already designed and is not concerned with creative alternatives of work.

On the other side of the spectrum lies cost plus fee (CPF) contracts which reduce the risk held by the contractor and shifts it to the owner. Figure 4-1 shows a gradual shift of risk from contractor to owner in seven different types of contracts.

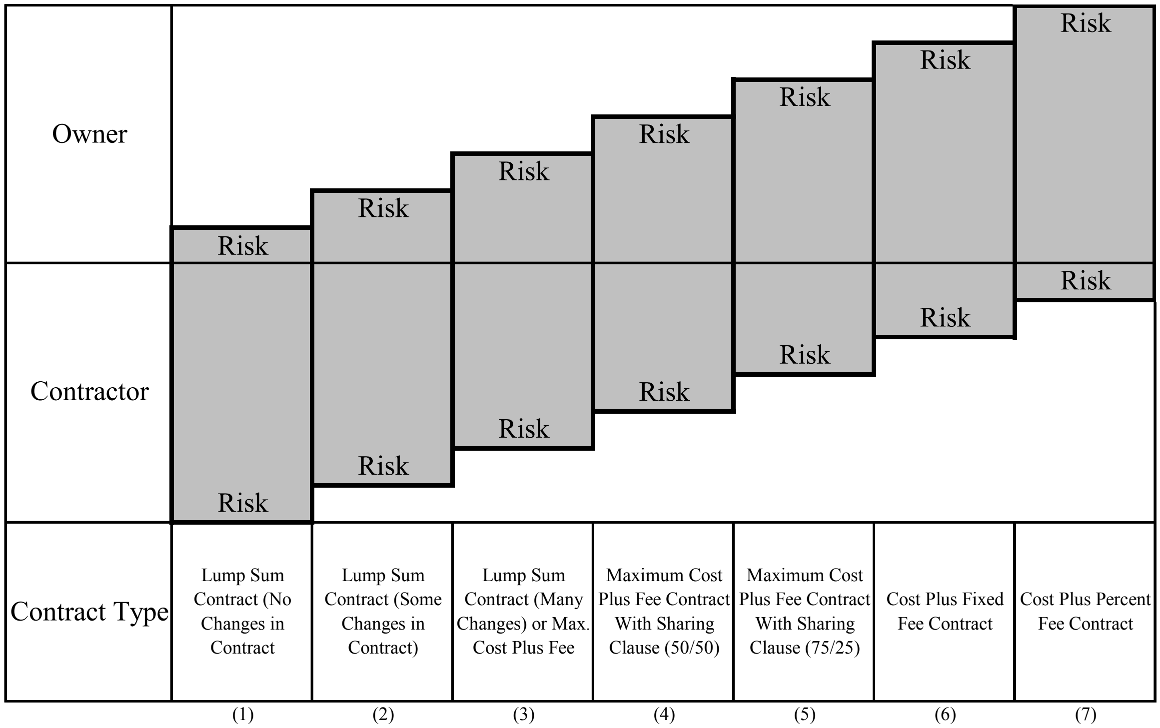



Figure 4-1 Scale of Contractual Risk Distribution (Collier 2001)

Notes:

(1) Only slight risk to owner.

(2) Some changes in contract change nature of lump-sum contract and introduce more risk of loss for owner.

(3) Many changes in contract may alter nature of contract and risk distribution considerably.

(4) Theoretical (not practical) distribution of risk about equal (50/50).

(5) Variation in risk distribution depends on many things, including level of maximum cost, distribution in sharing of savings/losses, etc.

(6) Some risk to contractor. (i.e., is fixed fee adequate if scope of contract increases?)

(7) Only slight risk to contractor. (i.e., is percent fee adequate?)

Figure 4-1 shows that the lump sum and cost plus percent fee contract lie on opposite sides of the contractual risk scale. The cost plus fee contract binds the owner to pay for all work completed plus a fee to cover operating overhead and profit. Here the owner takes on the majority of risk which is widely different from the lump sum contract (Berends and Dhillon 2004). Risk can be inversely proportional to the amount of design information available. If the owner has no design information available and if they want the work completed, they must agree to pay for all the costs increasing the risk to the owner. As more design information becomes available, bidders can make better estimates on the cost which reduces the risk to the owner. By entering into a cost plus fee contractor, the owner agrees to pay all of the costs and an additional fee but essentially puts himself at the mercy of the contractor. Therefore, an owner should only enter this type of contract if they have a good working relationship with the contractor. A cost plus fee contract calls for more trust and confidence between the owner and the contractor. If the contractor is efficient and careful, the owner can realize cost savings however, if the contractor is inefficient and careless, then owner can experience great financial trouble (Berends and Dhillon 2004).

Cost plus fee contracts use the items of work concept. Items of work are the basic units of construction used to estimate cost. A cost estimate is based on the breakdown of all the materials taken from the drawings and priced with a percentage added on for labor costs or man hours calculated priced at current wages. This type of cost estimate is typically done in the electrical and mechanical trades, however for most estimating it is not the basis for the bills of materials used in quantities method of contracting (Collier 2001). A good example of an item of work is a brick wall being constructed by a craftsman and a helper. The item of work is the unit of “brick wall built in place,” because the costs to build the wall can be isolated and linked to the wall versus the brick or mortar alone. The amount of square feet of wall built can then be tied to the amount materials, labor and equipment such as the scaffolding. Work is important in the determination of progress and payment throughout a construction project and is defined in standard contracts. According to AIA Document A201-1997, 1.1.3, “work” means the construction and services required by the Contract Documents, whether completed or partially completed, and includes all other labor, materials, equipment and services provided or to be provided by the contractor…” The term work deals with labor, materials, tools, equipment, and all other services required of the contractor in the contract. Work is one part of the contract and payment of the described work is another.

Figure 4-2 shows two ways to define the cost of work. Direct work is reimbursable costs which include, labor, material, tools and job overhead costs. An indirect cost is non-reimbursable and includes operating overhead costs and profit.

<table>
<tr><td rowspan="2">Indirect Costs</td><td colspan="3">Profit</td><td rowspan="2">Fee (%) or Lumpsum</td><td rowspan="4">Total Costs of Construction Work</td></tr>
<tr><td colspan="3">Operating Overhead Costs</td></tr>
<tr><td rowspan="2">Direct Costs</td><td colspan="3">Job Overhead Costs</td><td rowspan="2">Cost of Work (as defined in Cost Plus Fee Contract)</td></tr>
<tr><td>Material Costs of Items of Work</td><td>Labor Costs of Items of Work</td><td>Equipment Costs of Items of Work</td></tr>
</table>

Figure 4-2 Costs of Work (Collier 2001)

Direct costs are easily reported by the project and the specific site that it takes place at. Indirect costs are related to the construction company as a whole and all of its projects that it has underway. Direct costs are paid for by the owner in a cost plus fee contract.

While indirect costs are not directly reimbursed by the owner because they can not be attributed to a particular project and would exist even if the contractor had no projects. Indirect costs are considered the costs of doing business.

In a cost plus fee contract, a contractor's operating overhead costs and profit are collected in the fee whether it is a percentage of the direct work or a lump sum. While in a fixed firm price contract, these costs are collected in the form of a markup that the contractor places in the total cost of the contract. The difficulty in a cost plus fee contract is distinguishing between what constitutes job overhead costs and operating overhead costs (Clough and Sears 1994). Therefore, an owner must ensure that this is clearly stated in the contract otherwise, costs overruns are likely to occur. An owner therefore is very interested in all the direct costs incurred under a cost plus fee contract (Halpin and Woodhead 1998).

The contractor's main responsibility in a cost plus fee contract is to perform the work in accordance with the contract documents and properly record all direct costs to ensure prompt payment by the owner. Trust and confidence between the owner, designer and contractor must be present for a cost plus fee contract to be worthwhile and a bargain for all parties involved. The contractor should perform work as efficiently as possible and not incur needless direct costs. Therefore, the job should not be overstaffed; equipment and materials should be properly obtained at market prices and should be used in the best interest of the owner. It can be seen here that there is plenty of room for interpretation which enforces the idea that the owner should have a relatively good working relationship with a contractor prior to entering into a cost plus fee contract. The contractor is also responsible for keeping records of all reimbursable transactions to the satisfaction of the owner (Clough and Sears 1994). In addition, the contractor shall pay the costs to rectify any defective work that is installed.

The owner's responsibilities in a cost plus fee contract are similar to the lump sum or fixed price contract in that they will pay for work according to the terms of the contract, provide information and access to the site and provide a design team that will furnish information to the contractor. The owner's rights are also similar to the fixed price contract in that they can stop work with appropriate cause and they can terminate the contract. In a cost plus fee contract the owner usually has the right to do work that is otherwise neglected by the contractor or if the contractor fails to do the work correctly.

The designer's obligations under a cost plus fee contract mirror those of the firm fixed price contract in that they act as the owner's agent; he also acts as the interpreter of the contract and will seek proper performance of the contract by both the owner and the contractor. However, in a cost plus fee contract, the designer may be more involved with work at the site to include preparing working drawings and specifications during the progress of work but also because the contract is more flexible, the owner and contractor will look to the designer for more information. Therefore it is quite common for a designer to place a full time manager at the construction site to oversee a cost plus fee contract (Collier 2001).

The subcontractor's responsibilities are also similar to the firm fixed price contract in that they are typically lump sum contracts with the contractor. However, since the subcontracts are considered direct costs to the project, the owner is more interested in how those subcontracts are made. Typically the owner, designer and contractor are involved with selecting the subcontractors so they are all in agreement with who will be working on the site. A supplier's role is also similar to the firm fixed price contract, where the primary difference is the involvement of the owner in the selection process.

The advantage of a cost plus fee contract to the owner is work can start earlier with incomplete design information because they are accepting the risk. Therefore the owner can get work done in a situation where the firm fixed price contract would not get done. In addition, the type of contract is very flexible for the owner; however, it comes with the potential of very high prices. The biggest disadvantage is the owner does not know what the final price of the project will be. To reduce this risk, the owner should make it a priority to obtain as much complete design information as possible (Bennett 2003).

Unit price contract is another avenue for construction project procurement. Unit price typically refers to the common unit in which the building material is sold with a markup for overhead, contingency and profit (Bennett 2003). This type of contract works well with items that have typical measurement units. For example, excavation, fill materials and cast in place concrete are all measured in cubic yards. However, this method may not work well with structural steel where labor becomes a majority of the fee to put the item into place. In addition, steel installation does not have a standard of determining the units of measurement. Unit pricing reflects the average of direct and indirect costs or the total costs divided by the number of units installed. Unit prices are highly influenced by the amount of work that is to be installed. An inverse relationship exists where the unit price increases as the quantity of work decreases (Collier 2001). This type of contract is exists for a few different construction items like heavy construction such as pipeline installation, sewers, roads and dams and major site work that is contracted separately from a building.

The contractor's obligations under a unit price contract are unchanged from the previous two contracts which are to produce the work in accordance to the contract and to be reimbursed for that effort. The unit price contract is similar to the lump sum contract except that it separates out individual items of construction. Measurement of work accomplished is performed by both the owner and contractor. However, this situation can lead to miscommunication and disagreement on how much actual work was accomplished.

The owner's responsibility is essentially the same as the previous two contracts: duty to pay for accomplished work, provide information and access to the site and to retain a designer to provide information to the contractor. However, one major difference is that the owner has the ability to change the amount of work accomplished by each type of work and can typically alter this amount by as much as 15% of original contract quantities (Collier 2001).

The designer's obligations are similar to the previous two contracts; however, their most important role is to verify the quantities of work performed by the contractor. One fundamental responsibility of the designer is to verify the schedule of unit prices submitted with the contractors bid. They should check the bid for arithmetic accuracy, in addition to the amounts of the prices themselves, their appropriateness and relative magnitudes. This occurs because an experienced contractor may overprice some unit prices and under price other items knowing which ones may increase in work during the construction phase. This is also done by an experienced contractor to front load the project and to extract more money out of the preliminary tasks. The designer has the responsibility of ensuring that those situations do not occur on a construction project utilizing a unit price contract.

The main advantage of unit pricing is an owner can proceed ahead with work when quantities of work are not adequately determined. The main disadvantage is inaccurate unit prices can be submitted by the contractor which leads to serious cost overruns. In addition, unit price contracts are used with work that is highly variable such as excavation where subsurface soil conditions can change rapidly. With this uncertainty, the owner is at a disadvantage with the contractor and will typically have to succumb to his unit pricing to complete work or suffer major financial losses. For the contractor, this type of contract is similar to a lump sum contract except if they gamble correctly, they can front load the project and extract more funds out early (Bennett 2003).

The fourth type of contract uses the concept of relational contracting. Striving for strong relationships and fostering team building can lead to improved project performance (Egan 1998). Relational contracts place emphasis on building relationships between the owner, architect and general contractor which allows the team to explore potential future work together (Macneil 1974). In addition a relational contract allows for flexiblility, reduces transactional barriers and allows for a rational way of selecting project teams (Rahman and Kumaraswamy 2004). Zaghloul and Hartman (2003) observed that contractors add between 8% and 20% to their bid estimates to cover their perceptions of high risk and uncertainty in construction contracts.

Relational contracting is facilitated by five factors (Rahman et al. 2007).

1. Client and top management must support the initiative

2. Appropriate contractual incentives must be in place
3. Team objectives must be clearly stated and in alignment
4. Relationship-building protocols
5. Proper resource utilization

Lichtig (2005) has developed a contract that is currently being used by a major California health provider, Sutter Health. This contract has many differences compared to the above mentioned lump sum, cost plus fee and unit price contracts. First and foremost this contract uses a team performance contingency which is allocated to the project. This contingency is used by all the entire project team which changes the incentive during the construction phase. This allows money to cross organizational boundaries where the project delivery team shares in the contingency that is in reserve once the project is complete. In addition, this type of contract uses the concepts of Last Planner and requires built-in quality plans which are key concepts to Lean construction. Another aspect is that it incorporates downstream players in upstream decisions with the goal of reducing the issues that are encountered during the construction phase.

The types of contracts previously mentioned can impact how a project is finally delivered and it is believed that establishing trust among owners, architects and general contractors can facilitate project delivery. In addition, sharing and allowing funds to cross organizational barriers where the entire project delivery team experiences the pains and gains of cooperation will facilitate project delivery. Aligning the goals amongst the project delivery team also facilitates project delivery and effects how each of the players interact with each other.

Changes in projects can be defined as any event that causes a modification in the original scope, execution time, cost, and/or quality of work (Revay 2003). These changes are further defined by five categories: change in scope, differing site conditions, delays, suspensions, and acceleration (Sweet 2004). It has been shown that increased change order hours have a direct impact on contract hours (Leonard 1987). Research has also shown that the greater amount of change, the less efficient workers are on a project and late project change has a greater effect on labor productivity than early change (Ibbs 2005). Changes can take place at any phase of a project. However, determining how to quantify the changes that effect contractors and subcontractors is a difficult task. One example deals with how changes are dealt with in a mechanical contractor. In this example a healthcare facility is being constructed and changes to the mechanical systems were flowed down to the mechanical contractor. Once this change was known, the detailing portion of the mechanical contractor tried to capture the change, rework shop drawings and reorder the material. This material would then be fabricated at the shop and sent to the field for installation. However, this did not have the desired effect because the field was getting confused on what materials could and could not be installed resulting in situations where the mechanical work had to be installed twice. Therefore, the mechanical contractor decided to implement a different model that forced all of the changes and rework to be done and collected by the field. No additional effort by the detailing entity would be done unless called for from the field. This resulted in better cost tracking for changes and rework. In this case study, once the costs of the changes and rework reached the owner, the owner decided to not go through with the stated changes because the cost increase was too large.

Construction contracts play a major role in how people behave on projects. Changes can be a major source of funding to contractors and can significantly increase profits. Typically, changes are quantified by the total cost to install a new product. However, the full cost of the change may not be captured because it may not include the total time for a detailer to catch what the change is, to re-accomplish and de-conflict the drawings, and then re-fabricate the item. Owners do not pay for additional work a contractor does behind the scenes. This is the phenomenon of not getting credit for correcting errors that never happen (Repenning and Sterman 2001). However, by pushing changes to the site, the costs are more explicit and in some instances will be higher than the owner is willing to pay for.

"By building to an agreed upon set of drawings, the cost of change becomes more transparent when the owner can physically see us replacing material with the change that they requested (Slane 2008)."

Therefore, with a traditional contract and risk-and-reward system in place, it is in the best interest of the mechanical contractor to delay dealing with the changes to site installation.

## 4.5 Detailing, Fabrication, and Installation DES Model

Figure 4-3 shows a flow diagram for a mechanical contractor from when it receives approved design drawings to final installation of product. Upstream pressure occurs because design drawings are due to the state agency for approval. As mentioned, this review process can be lengthy, therefore, to ensure drawings can be approved; the design engineers push to submit as early as possible. As a result, the design drawings may be adequate for permitting purposes, but even so, they may lack the required information for a contractor to fully detail the mechanical system. This results in the mechanical contractor receiving multiple sets of drawings which then have to be reworked to get the desired shop drawings for designer (architect and engineer or A&E) approval. The process in the dashed box can take up to 10 weeks, with each rework cycle adding three weeks to the process.

Downstream pressure on the mechanical contractor occurs from the general contractor's date to place concrete for the healthcare facility floor slabs. The reason is that it is much more economical to drop inserts (straps from which duct will be hung) through metal decking before the concrete slab is cast over it, than to drill and secure straps into a hardened concrete slab, but this means that duct locations have to be locked in prior to concrete placing. From this date, the mechanical contractor typically tries to start the insert drawing four weeks in advance with the goal of having a complete insert drawing two weeks prior to deck placement. However, insert drawings cannot be completed until the layout of the mechanical system is finalized. If the layout continues to change, the insert drawings cannot be completed. The mechanical contractor wrestles with these two pressures constantly throughout project construction.

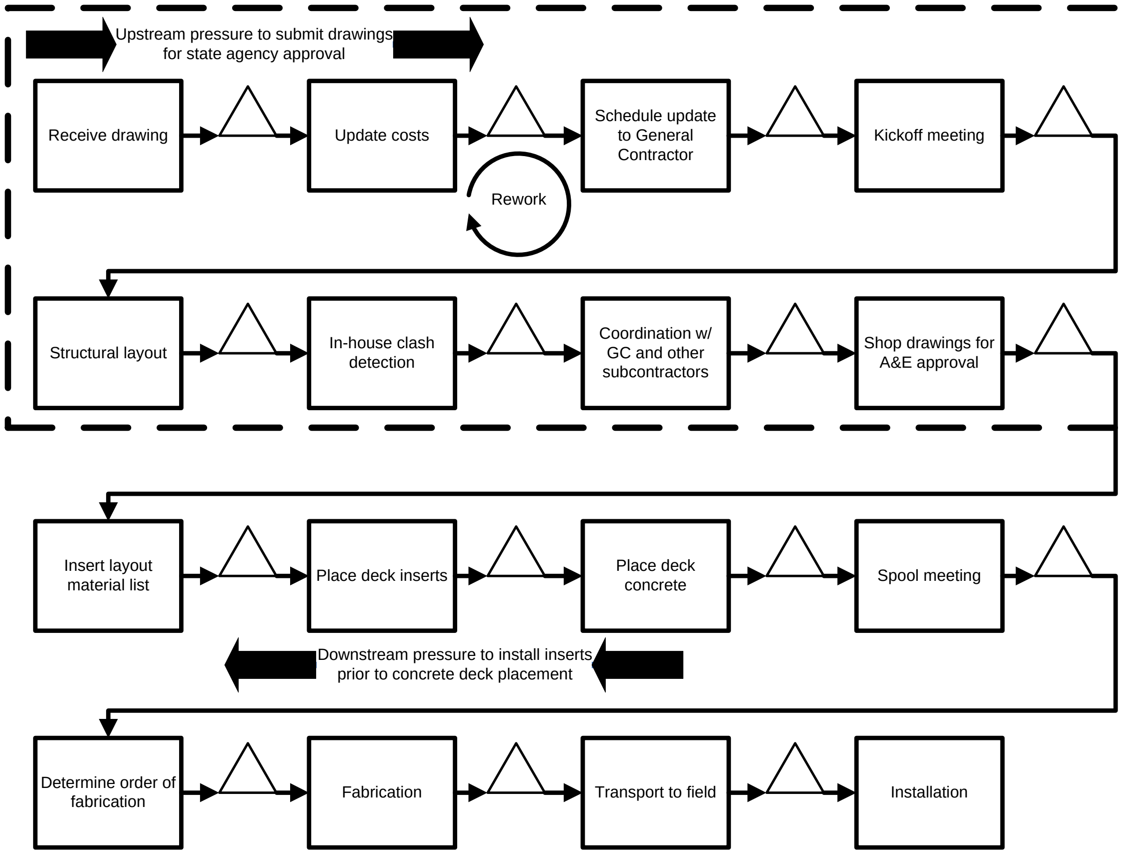



Figure 4-3 Flow Diagram of Mechanical Contractor Process

The model developed shows work that flows through three stages. First, the mechanical contractor details the required parts and pieces from the design drawings. This is an extensive effort to take single line design drawings and fill in three dimensional pipe and ductwork that shows all of the pieces needed for actual construction. This work has been facilitated by the use of computer renderings showing how pipe and ductwork is installed in a facility. For a large project, the mechanical contractor is responsible for coordinating the drawings with outside contractors, such as fire, life, and safety, electrical and structural engineers. Once the drawings have been coordinated, the materials can then be fabricated for site installation. This contractor uses in-house capabilities to produce the majority of project materials. Once fabricated, parts can be shipped and installed.

Site preparatory work must be completed prior to installation. In the example of ductwork, hangers and straps are inserted a few days prior to placement of concrete. However, the layout of the ductwork occurs many months prior to fabrication. During that time, design changes will invalidate existing layouts. In an effort to reduce rework, the mechanical contractor tries to detail the hangers and straps at the last responsible moment. Their goal is to have fully coordinated insert drawings two weeks prior to concrete placement. These inserts are then fabricated and installed 3-5 days prior to concrete placement. Once concrete is placed, if the layout changes, the mechanical contractor must drill into the concrete to place new hangers.

In each of the phases of work, changes can occur. Figure 4-4 shows the potential rework caused by a change introduced during the project timeline. Each detail has to be looked at to determine if it was affected. There could be fabrication changes and on-site material changes as well. The figure shows the potential for large amount of rework when a change occurs.

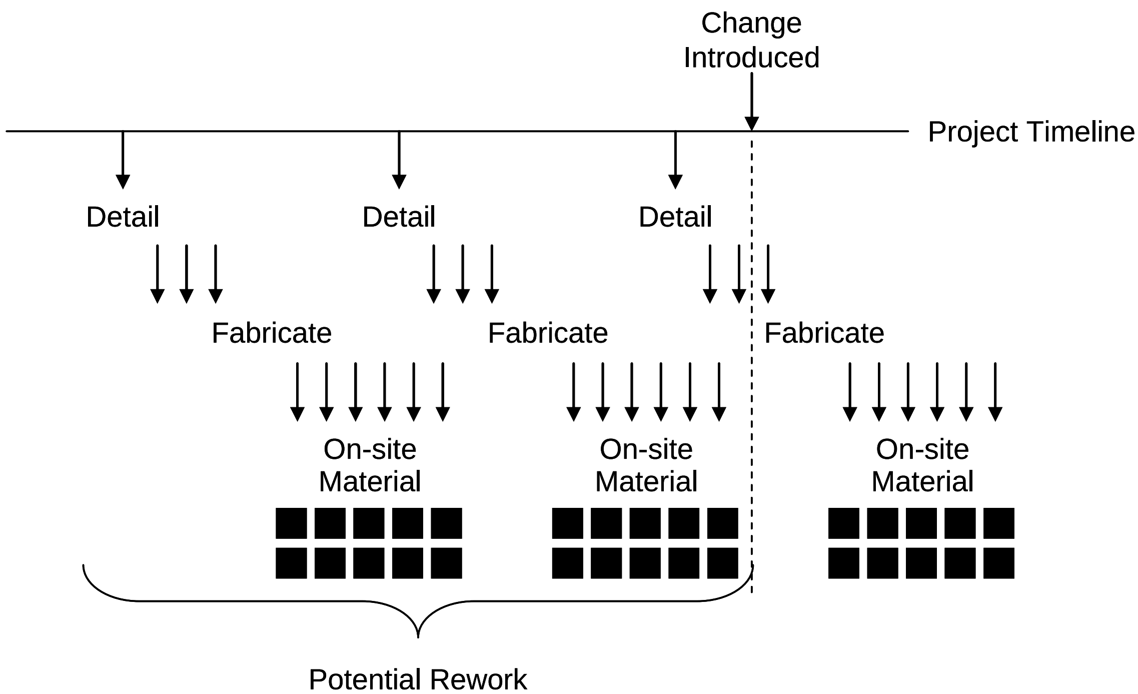



Figure 4-4 Rework Potential

In the detailing phase, many times, the mechanical engineer of record (i.e., the licensed engineer) is not done with their design, leaving gaps of information for which the detailers can not finalize. If the detailer has completed the drawings and the mechanical engineer makes changes, then the drawings have to be re-detailed. This takes extra effort by the detailers to first interpret what the changes are and determine how the drawings change. These changes can be small or large and may take time for the detailers to fully understand and capture all of the changes.

Changes can also occur in the fabrication phase when an item is in the midst of being made and changes to the original design are found. This requires the item to be re-detailed and re-fabricated. Changes can also be found when the item is on-site and the design changes, again, this requires the item to be re-detailed, re-fabricated and re-sent to the site. Figure 4-5 captures this situation in a discrete event simulation model.

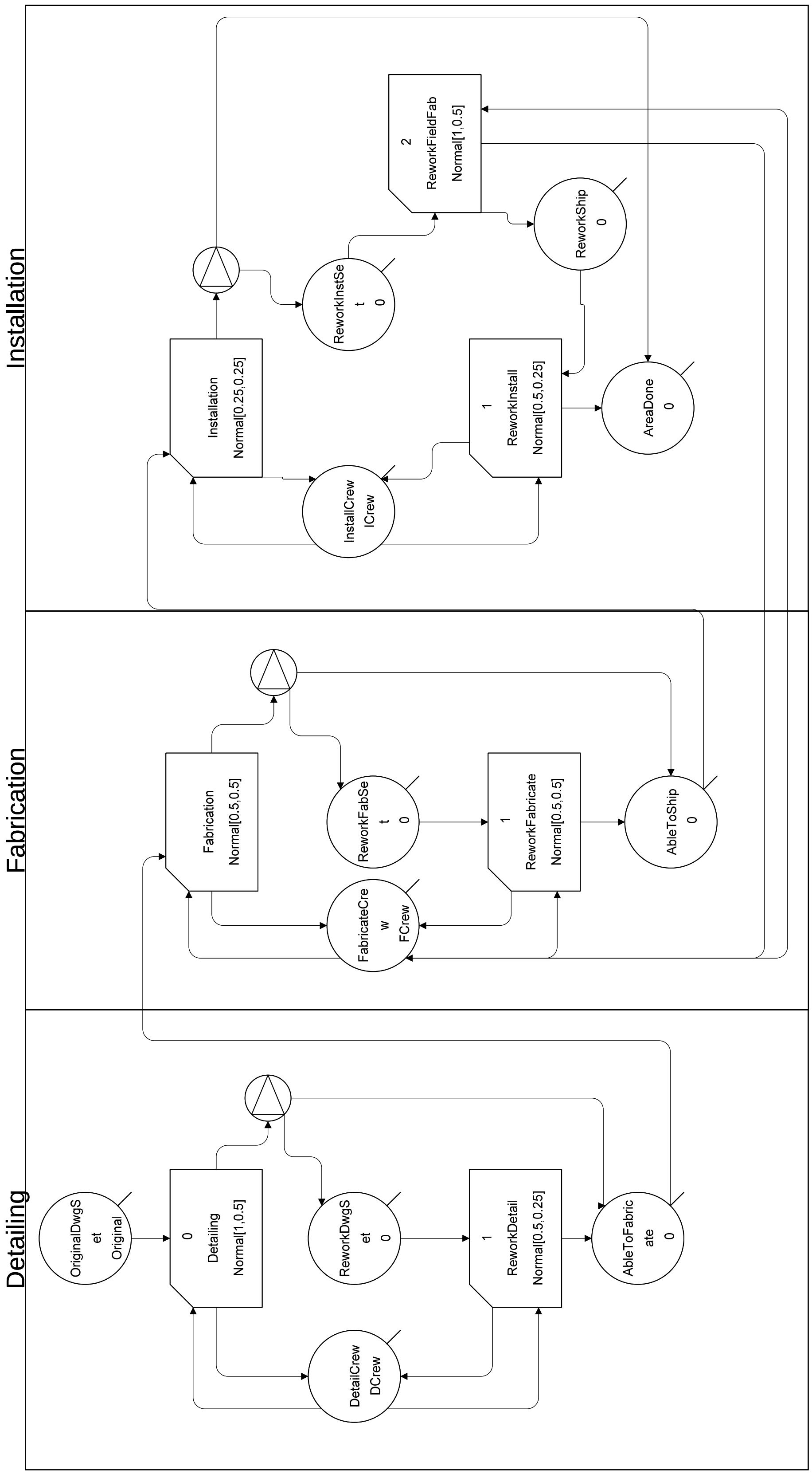



Figure 4-5 Discrete Event Simulation of Detailing, Fabrication, and Installation

As mentioned, within healthcare facility construction, the permitting process may require the design engineers to complete a back-check by clarifying or correcting the design. However, the mechanical contractor, in an effort to expedite the process and meet the pressure of the concrete placement schedule, may detail from the original drawings and deal with the changes as they arise through each of the back-checks. This creates rework for the detailers, fabricators, and installers. The model simulates this scenario by allowing rework to occur at each of the phases.

Table 4-1 shows the input parameters used for an iteration of the model. It describes that there are 4,500 T (10,000 lbs) of material that must be completed. Rework has been set to zero percent, which means that as each piece of resource flows through the decision fork, none of the material will be required to be reworked. The model user can easily reset this parameter to study the impact of different degrees of rework. It is important to note that in this model, an item is only reworked once and then allowed to continue (a more complex model could be developed to include repeated cycling). The model allows you to input how many personnel are available to accomplish each stage of work in detailing, fabrication, and installation. It also allows you to determine how many workers are needed to accomplish each work package; in this scenario one worker is required at each stage. Finally, the model allows the user to vary the batch size at each stage. When batch size increases, the modeler must also change the time in each of the production activities, otherwise, it appears that workers can accomplish more work items per unit time.

| | | | | | |
|---|---|---|---|---|---|
| Original | Original Drawing Set | 10000 | FCrew | Number of fabricators available | 1 |
| ReworkDet | Percentage of Rework (Detailing) | 0 | FCrewReq | Fabrication Crew Required | 1 |
| ReworkFab | Percentage of Rework (Fabrication) | 0 | ICrew | Number of installers available | 1 |
| ReworkIns | Percentage of Rework (Installation) | 0 | ICrewReq | Install Crew Required | 1 |
| DCrew | Number of detailers available | 1 | FBatch | Fabricate batch size | 1 |
| DCrewReq | Detail Crew Required | 1 | DBatch | Detail batch size | 1 |

Table 4-1 Model Input Parameters (No Rework)

In the detailing phase (figure 4-5), the first queue holds the total amount of material needed for the project. The work flows into a Combi called detailing and then one worker is drawn from a pool of workers and the item is detailed. The work then flows into a decision fork to determine if the item passes a quality check or has to be reworked. If the item passes, the work package flows into the able to fabricate queue. If it has to be reworked it flows into a Combi that draws from the available manpower and completes the rework.

This framework is replicated in the stages of fabrication and installation as shown in figure 4-5. However, items requiring rework in site installation have to be re-fabricated, so the item returns back to fabrication and once completed it is shipped back to the site for installation.

## 4.6 Analysis and Results

A line of balance chart shows the relative speeds of these sub-processes. Steep lines represent fast processes. Less steep lines represent slower processes. The horizontal distance between the top of a line to the bottom of the next line represents the relative delay to the start of the following process. Large distances represent longer delays while shorter ones represent processes that start right after each other.

Figure 4-6 shows a line of balance of the data collected from the model. It has four scenarios: (1) no rework (ideal situation), (2) 10% rework in each phase, (3) 20% rework in installation only, and (4) 30% rework in installation only. Scenarios (3) and (4) represent the paradigm of pushing changes to the installation phase.

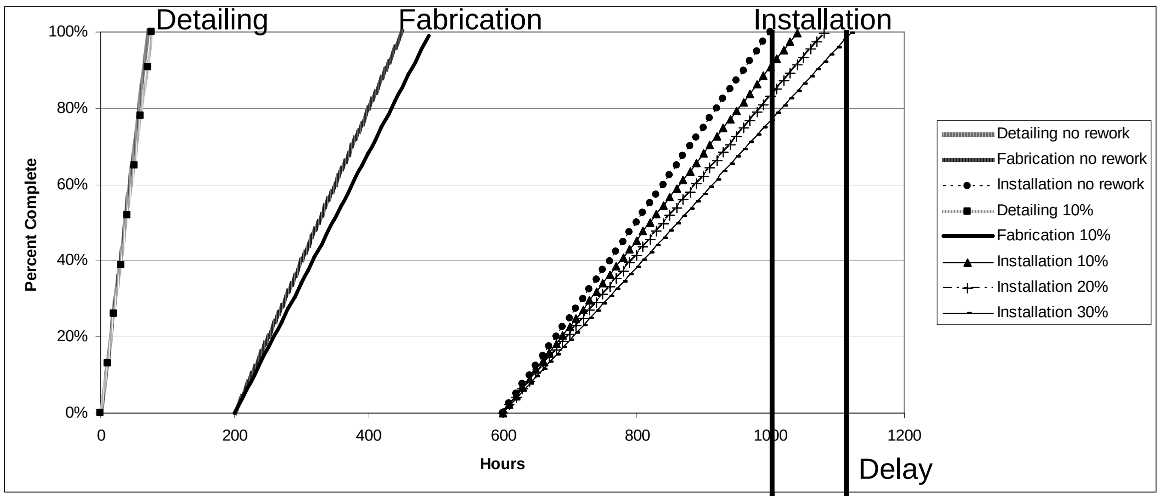



Figure 4-6 Line of Balance for Detailing, Fabrication, and Installation

In figure 4-6, detailing can occur rapidly if no changes to the design exist and the team is allowed to go through the entire set of drawings. Fabrication of items is also a steep line, because once requested, mechanical parts can be produced rapidly. This figure also shows that the detailing and fabrication phases could be delayed and do not affect the start of installation. Installation, however, is a less steep line in comparison to detailing and installation.

The concept the mechanical contractor implemented was to wait to work on the changes which reduced variation. The cost of rework, then, can be revealed through modelling as shown by the two vertical lines in figure 4-6. One line at 1,000 hours, the other at 1,150 hours, translates into dollars by multiplying the difference, 150 hours by an hourly labor rate. Assuming the man hour rate is 65 $/hr, the cost of change is $9,750.

I developed a discrete event simulation model that begins to quantify process costs of rework in construction and highlights the need to improve process management on projects. This research shows that it can be more efficient to let changes occur at site installation and avoid them in the detailing and fabrication phases, especially when a traditional contract and risk-and-reward system are being used. In the absence of final design drawings, mechanical contractors can follow the process described in this chapter as a way to reduce variation.

## 4.7 Limitations

Three limitations are identified for workflow research of a mechanical subcontractor.

1. The case study is of only one mechanical subcontractor and may not be representative of the entire population of mechanical contractors dealing with healthcare facility construction in northern California.
2. Data is representative of a generic resource. No distinction was made for different types of mechanical work that is produced by the contractor.
3. The rework cycle for each of the phases is allowed to occur only once. Also, the rework cycle is not dynamic; it is a static percentage when evaluating each piece of work for rework. However, this situation is addressed in chapter 5.

## 4.8 Section Acknowledgments

This work was funded in part by industry contributions made in support of the Project Production Systems Laboratory at U.C. Berkeley. All support is gratefully appreciated.

# 5. UNDERSTANDING DEMAND AND CAPACITY USING SIMULATION

## 5.1 Section Abstract

The purpose of this section is to illustrate the complexity that rework adds to a simple production process. The production process includes an initial review activity, a decision fork, and a re-review activity. Simulation models show the impact of rework on this simple production process and how it affects the time to permit. I discuss three models in this section: (1) a simulation model where rework is allowed to occur only once, (2) a simulation model where rework is allowed to occur three times, and (3) a simulation model where rework is allowed to occur indefinitely. For one rework cycle, to stabilize the simulation stabilizes two review resources are required for the entire range of the likelihood of rework. For multiple rework cycles, the number of resources required to stabilize the system increases dramatically. While for three rework cycles, the resources required to stabilize the system lies in between. This section illustrates the trade-off between stabilizing the system and the amount of rework that occurs within the system. The simulation models also illustrate that the increase in rework requires substantially more review resources to stabilize the system.

## 5.2 Background and Scope

This chapter describes the model of a simple production system developed to illustrate the complexity that rework adds to production systems. The model shows a state permitting agency receiving projects and reviewing them. If errors are detected, rework is necessary, if not, the projects are approved. This model is to provide intuition on how rework affects a production system. A more complex and applied case study that expands on the simple model discussed here is presented in chapter 6.

## 5.3 Simulation of One Rework Cycle

Figure 5-1 shows a simple production system, that models project reviews. Projects enter the review process at a constant rate of one per day. All projects are identical in nature. Once in the system, a reviewer conducts the Initial Review. Once this activity is complete, the project moves into a decision node to determine if rework is required. If rework is not required, the projects flow into the Complete queue. If rework is required, the projects flow into the Re-Review activity. Once there, the Re-Review activity takes priority over the Initial Review activity and when available, a review resource re-reviews the projects. Upon completion, the projects flow into the Complete queue. This simulation allows only one rework cycle to occur.

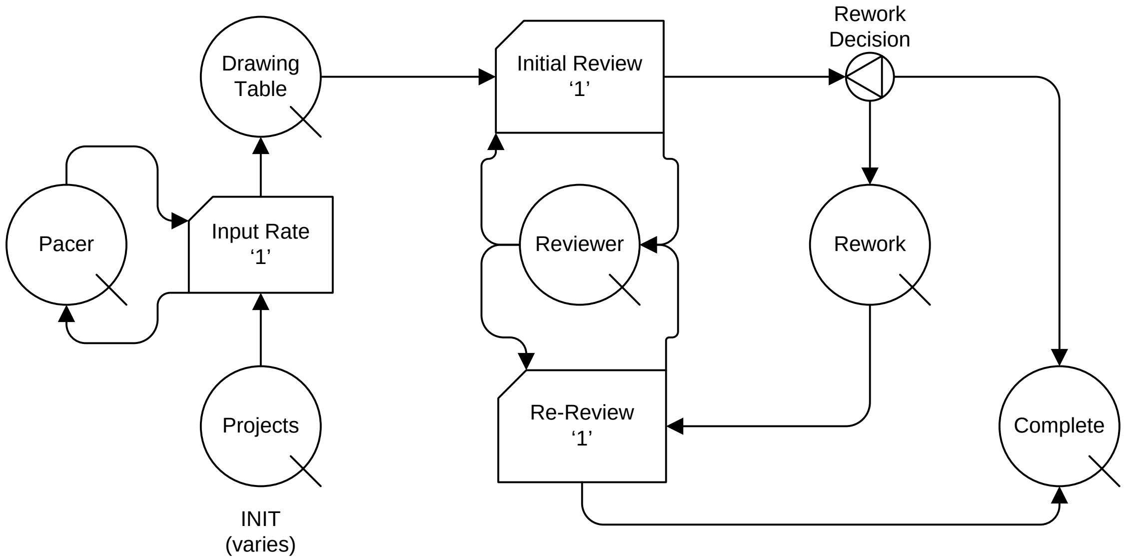



Figure 5-1 Rework Cycle (One Rework Cycle)

## 5.4 Simulation of Three Rework Cycles

The second model is similar to the model presented in figure 5-1, except that three rework cycles are allowed to occur instead of one. Each additional rework cycle takes priority for re-review over the previous rework cycle following the first in first out (FIFO) queueing logic.

## 5.5 Simulation of Multiple Rework Cycles

The third model also is similar to the first two but now rework cycles are allowed to occur indefinitely (figure 5-2). Once a project is reviewed it enters a decision node to determine if rework is required. If rework is not required, the project flows into the Complete queue. If rework is required, the project flows into the Re-Review activity. Once again, this activity takes priority over the Initial Review activity. However, once the activity is completed, the project again enters the decision node to determine if the project requires rework. In this simulation, the percentage of rework assigned to the Rework Decision does not change.

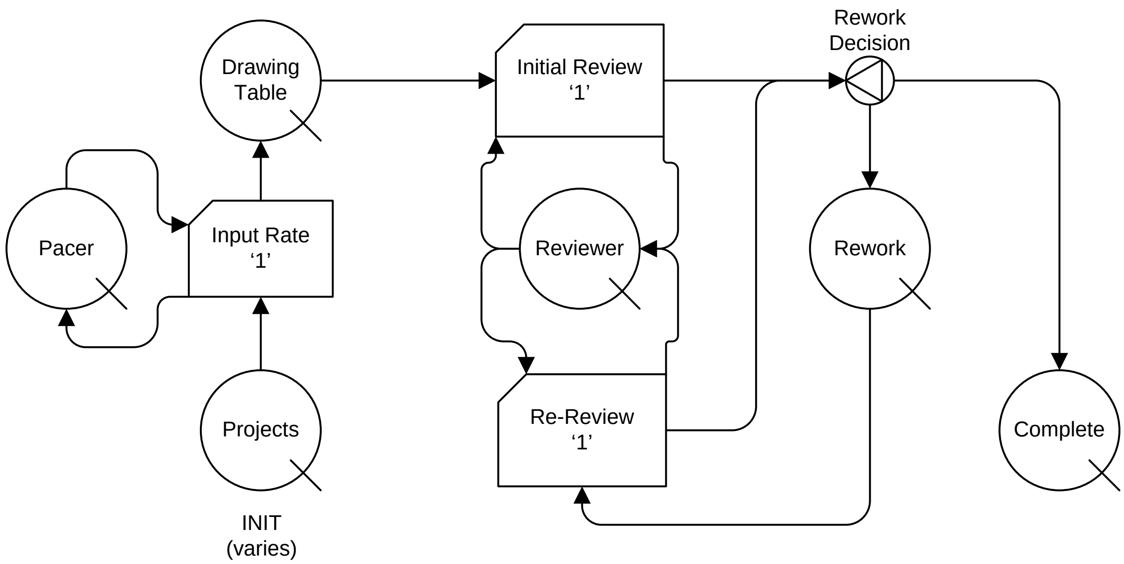



Figure 5-2 Basic Rework (Multiple Rework Cycles)

## 5.5 Demand and Capacity Analysis

Figure 5-3 shows output for one rework cycle. It shows the Drawing Table queue size versus time. In this example, with one rework cycle and 100% rework, each project requires two days to travel through the system. If only one reviewer is available, the Drawing Table queue increases by one every two days. Therefore, with an inflow of 1 project per day to the Drawing Table, the resulting Drawing Table queue size will be 500 after 1,000 days.

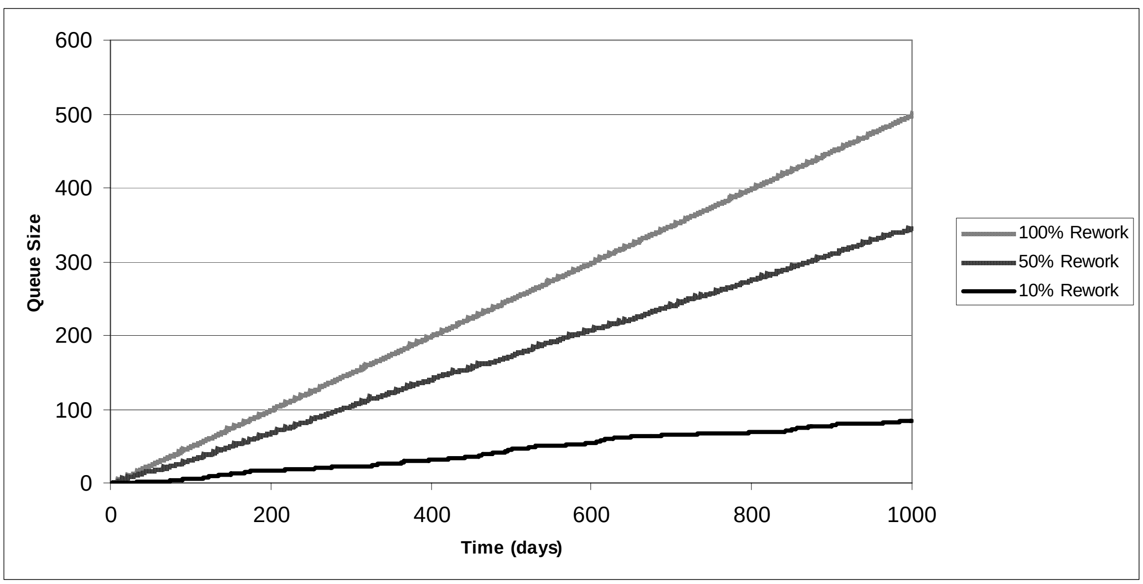



Figure 5-3 Drawing Table Queue vs. Time (One Rework Cycle)

Figure 5-4 shows the Drawing Table queue size versus time for multiple rework cycles. As rework approaches 100%, the Drawing Table queue size will grow by one each day. This occurs because projects remain in the system almost indefinitely and therefore, the queue will grow at the same rate as the inflow of projects, which in this situation is one project per day.

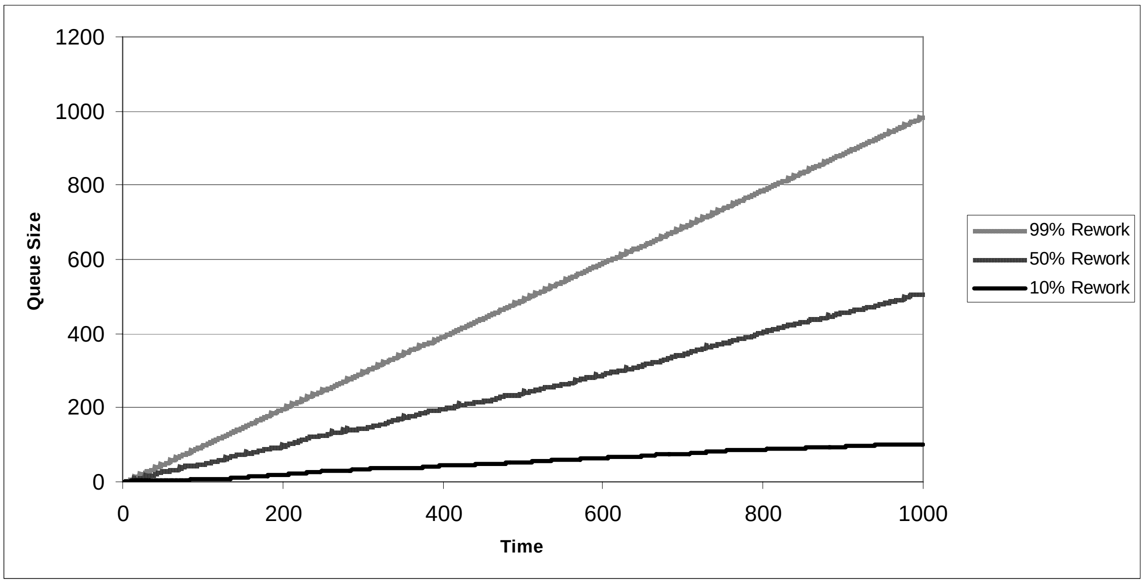



Figure 5-4 Drawing Table Queue vs. Time (Multiple Rework Cycles)

Figure 5-5 shows lead time to complete project review versus Drawing Table queue size for one rework cycle. It shows similar information as figure 5-3. As the Drawing Table queue size increases, the time for a project to proceed through the system also increases. For example for a scenario of 100% rework, the lead time for each project increases by two days for each addition to the queue. The 50% and 10% lines are truncated because the simulation time is the same for each scenario. The truncation of the 50% and 10% lines show the lead time for completion at the end of the simulation time.

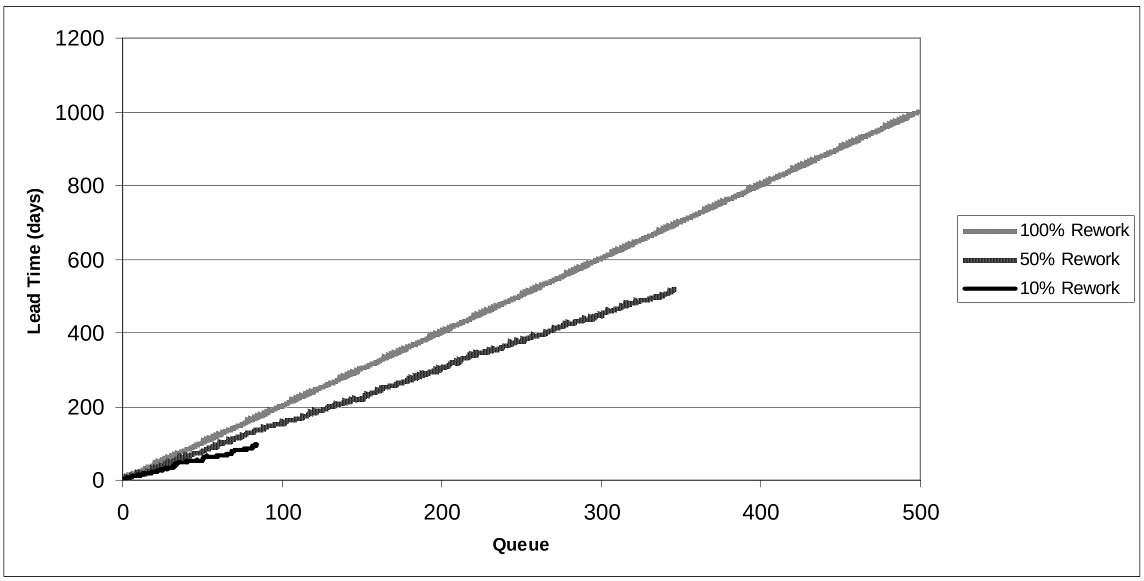



Figure 5-5 Lead Time to Complete Project Review vs. Drawing Table Queue (One Rework Cycle)

Figure 5-6 shows the lead time to complete project review versus Drawing Table queue size for multiple rework cycles. Due to the large differences in lead times, the y-axis is converted to a logarithmic scale to show the different rates of increase to lead time due to the rework rate. As the likelihood of rework approaches 100%, the lead time grows significantly, again, because projects remain in the system indefinitely.

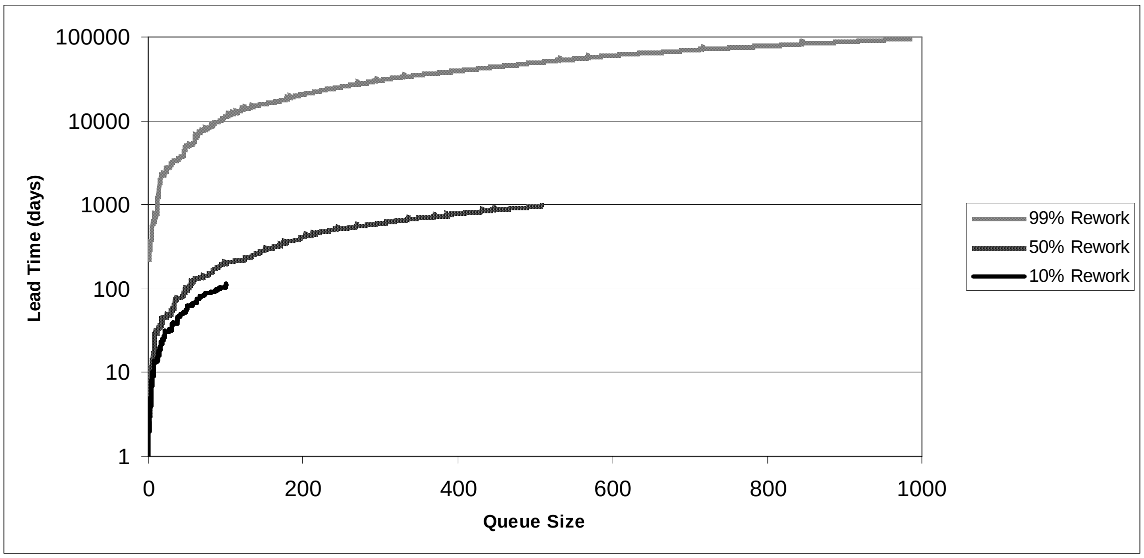



Figure 5-6 Lead Time to Complete Project Review vs. Drawing Table Queue Size (Multiple Rework Cycles)

Figure 5-7 shows the lead time to complete project review versus simulation time. For one rework cycle, the increase in time is linear and the maximum rate of lead time increase is limited by the inflow of projects. This means that for 100% rework, the lead time increases by one day with each additional day that passes.

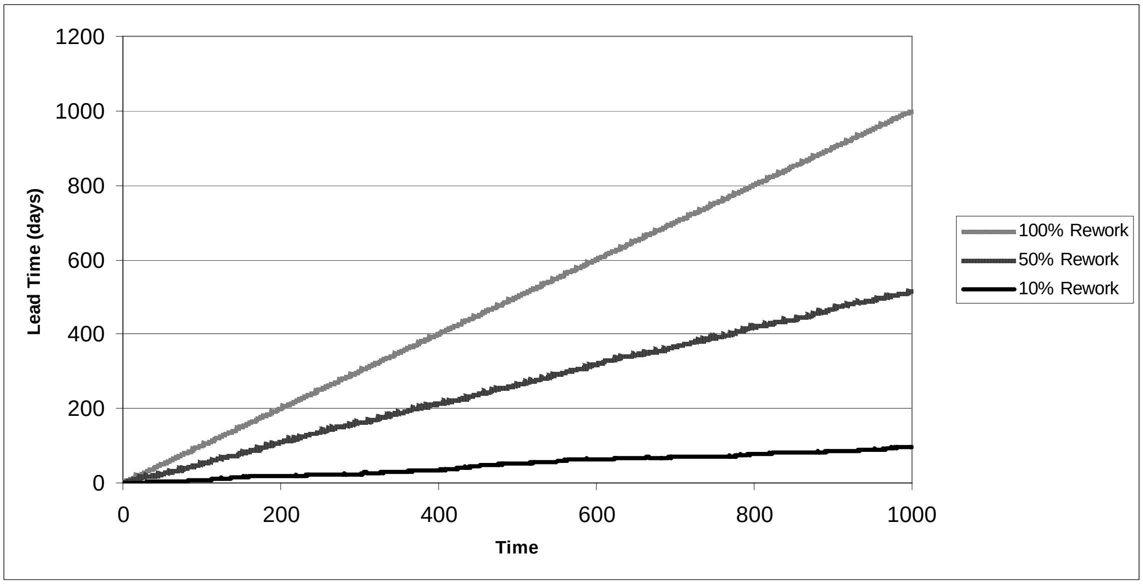



Figure 5-7 Lead Time to Complete Project Review vs. Simulation Time (One Rework Cycle)

Figure 5-8 shows lead time to complete project review versus simulation time for multiple rework cycles and shows the lead time will continue to increase as rework approaches 100%. Due to the large differences in lead times, the y-axis is converted to a logarithmic scale to show the different rates of increase to lead time due to the rework rate. This is similar to figure 5-6, as rework approaches 100%, projects remain in the system almost indefinitely.

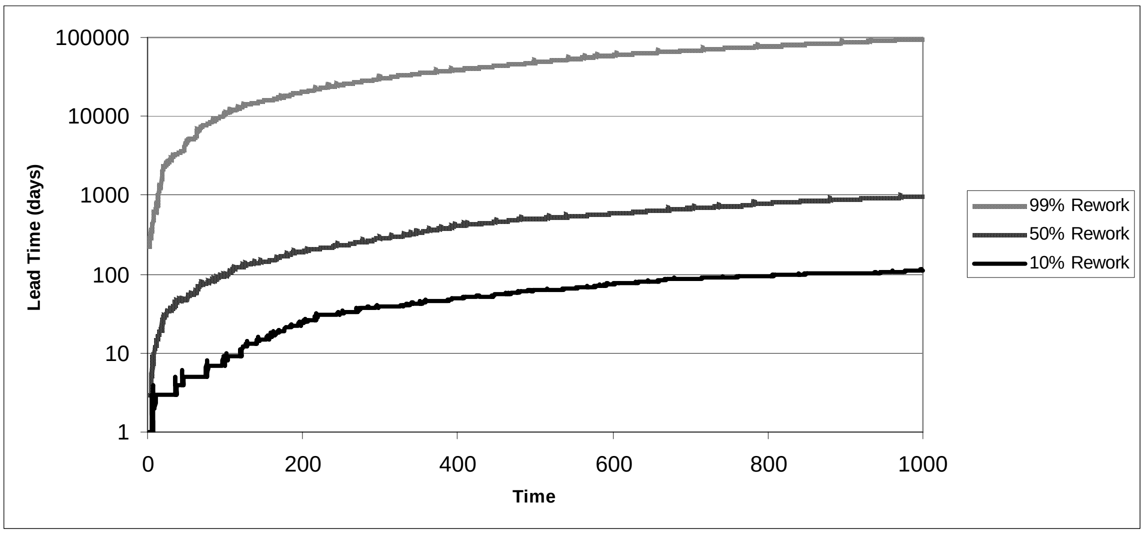



Figure 5-8 Lead Time to Complete Project Review vs. Time (Multiple Rework Cycles)

## 5.6 Resource Stabilization Analysis

Figure 5-9 shows the resources required to stabilize the system when rework is allowed to occur indefinitely. A stabilized system is defined here as one in which the queue size and lead time do not grow indefinitely over time: it remains in control when enough resources are allocated to offset the increase in the likelihood of rework. On the x-axis is the likelihood of rework, on the y-axis, the number of review resources required to stabilize the number in the Drawing Table queue and lead time to complete project review. Figure 5-9 shows that the number of resources dramatically increases as the likelihood of rework approaches 100%.

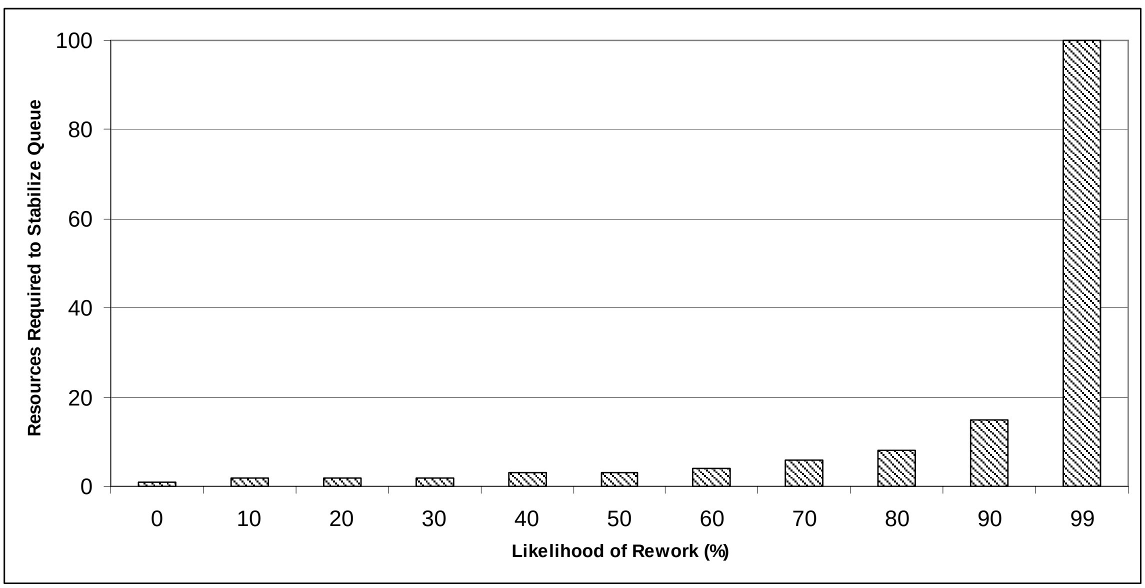



Figure 5-9 Resources to Stabilize System (Multiple Rework Cycles)

Figure 5-10 shows the number of resources required to stabilize the system for one, three, and multiple rework cycles up to 90% rework. For one rework cycle, only two resources are required to stabilize the system for any likelihood of rework. For multiple rework cycles, the number of required resources increases dramatically when the likelihood of rework increases. For three rework cycles, the number of resources required falls in between, which is an expected outcome.

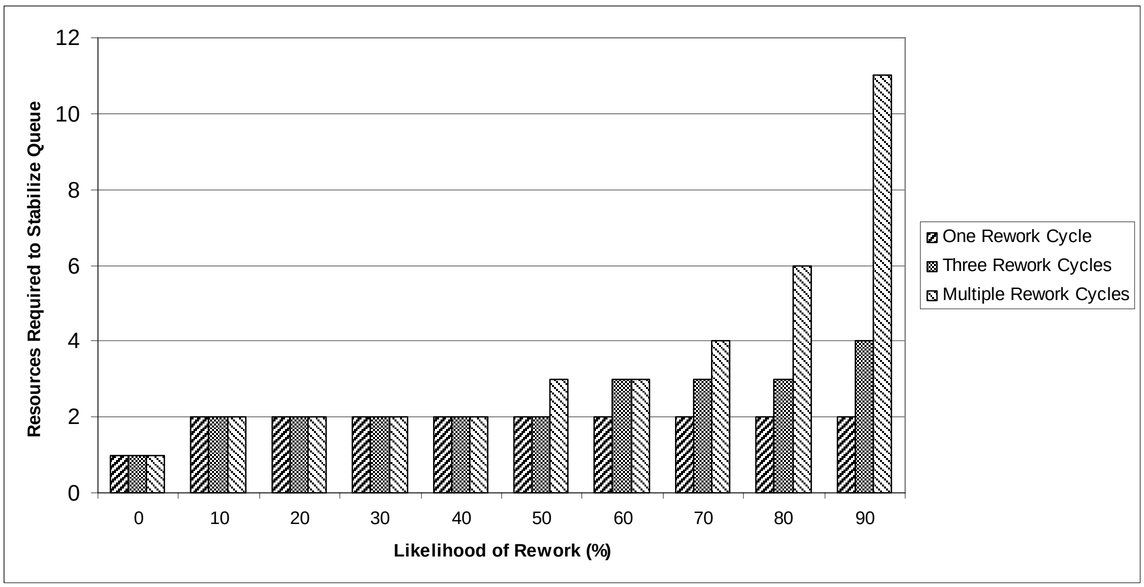



Figure 5-10 Resources to Stabilize System (Multiple Rework Cycles)

Figure 5-11 shows an example of what queue stabilization resembles for 80% rework, 3 reviewers, and 3 rework cycles. It shows that the queue size does vary over time, ranging between 0 and 15 projects.

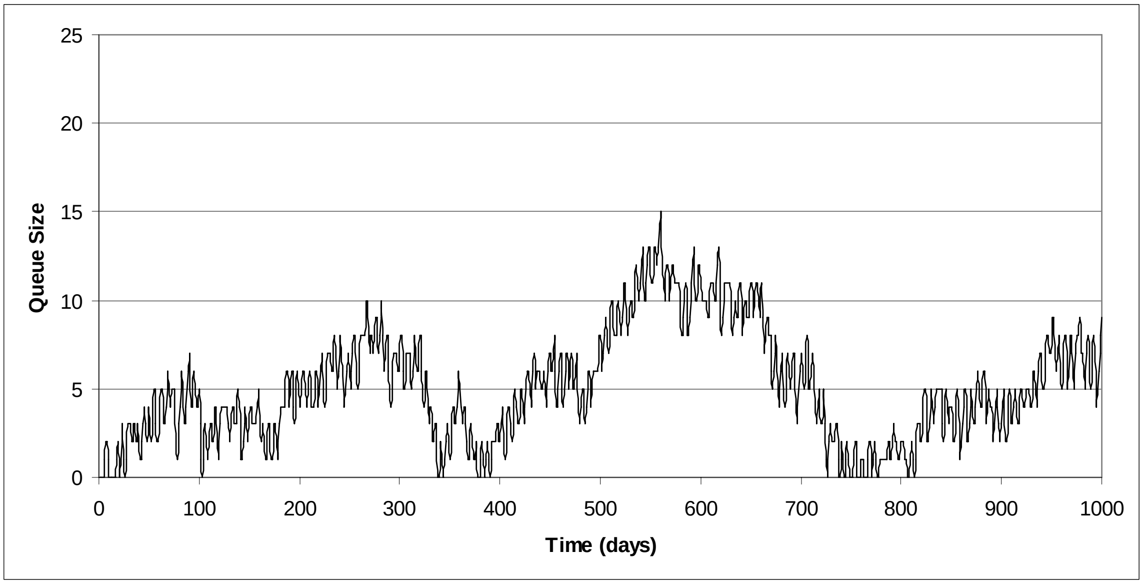



Figure 5-11 Queue Stabilization (80% Rework, 3 Reviewers, 3 Rework Cycles)

Figure 5-12 shows an example of what queue stabilization resembles for 80% rework, 6 reviewers and multiple rework cycles. It shows that the queue size varies over time, ranging from 0 and 23 projects. It is expected that the queue size would have the possibility of being larger than shown in figure 5-11 because rework is allowed to occur indefinitely, leaving more projects in the queue. The indefinite rework cycle is also the reason why more review resources are required to stabilize the system.

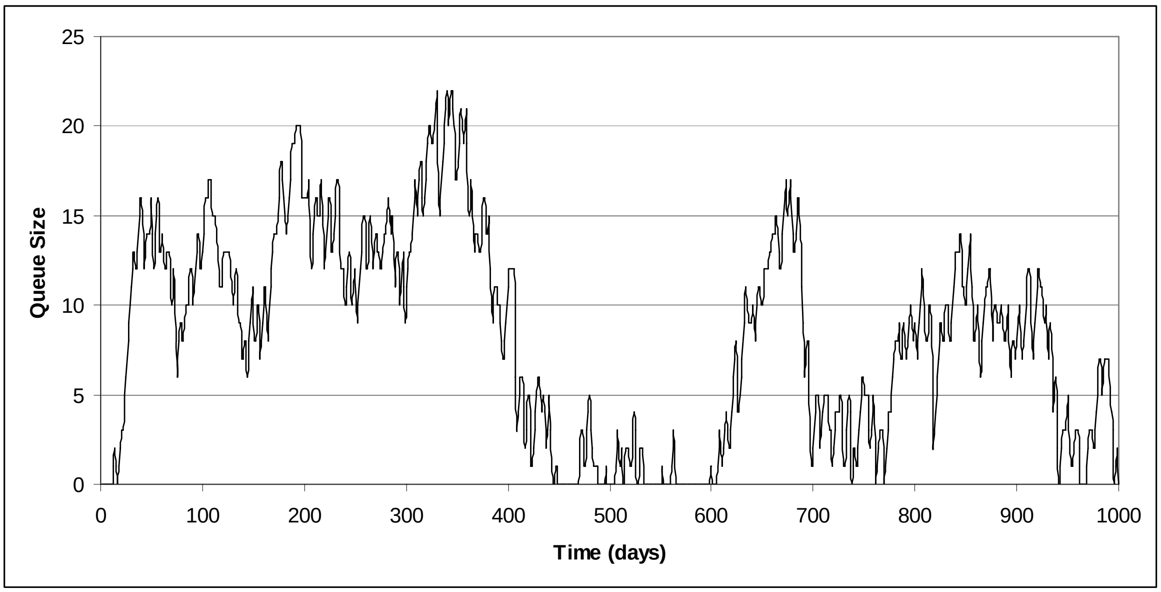



Figure 5-12 Queue Stabilization (80% Rework, 6 Reviewers, Multiple Rework Cycles)

Figures 5-13 to 5-16 illustrate the impact that small increases in resource capacity can have on queue size and lead time. Figures 5-13 and 5-14 show the queue size versus time for a series of 30 computer simulations. The middle line in each figure represents the mean queue size over time. The dark lines above and below the mean line represent one standard deviation. It shows that with five resources, the queue size continues to grow. However, figure 5-14 shows that by adding one resource, totaling six resources, the queue size stabilizes between two and four.

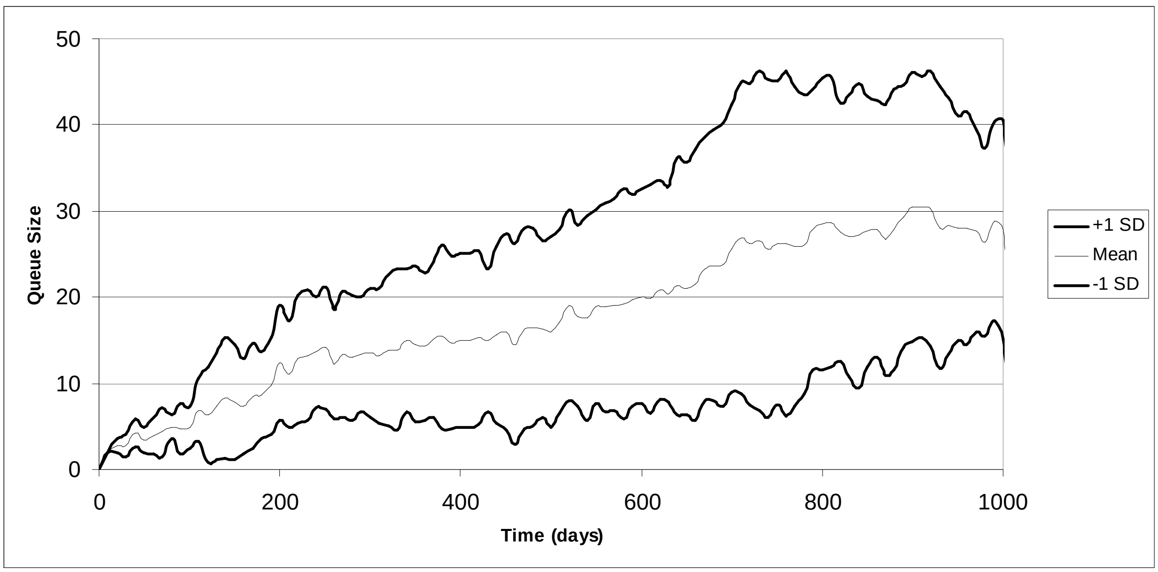



Figure 5-13 Queue Stabilization (80% Rework, 5 Reviewers, Multiple Rework Cycles, 30 Iterations)

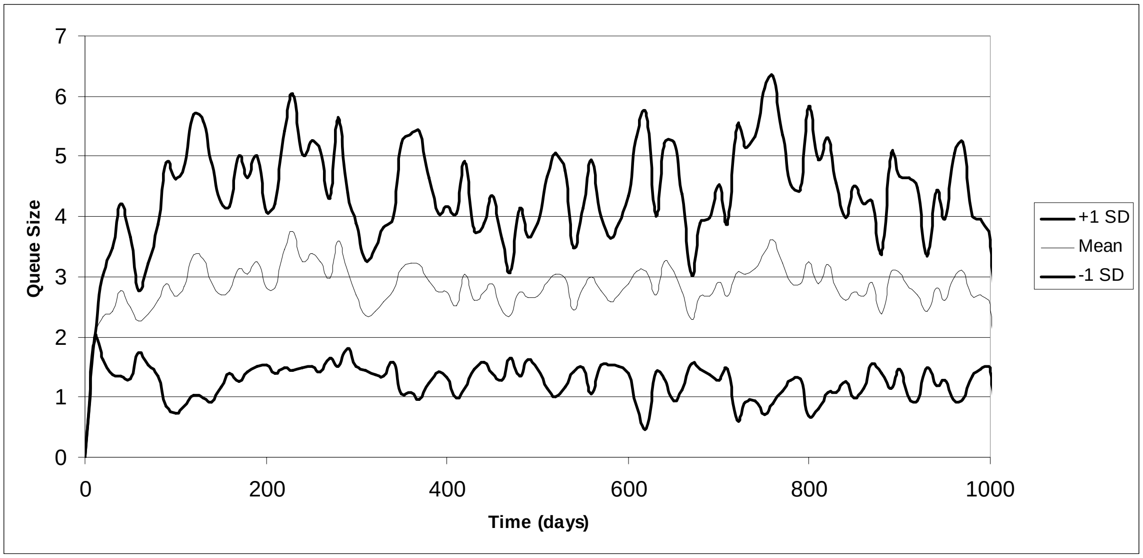



Figure 5-14 Queue Stabilization (80% Rework, 6 Reviewers, Multiple Rework Cycles, 30 Iterations)

Figures 5-15 and 5-16 show the lead time versus time for a series of 30 computer simulations. The middle line in each figure represents the mean lead time over time. The dark lines above and below the mean line represent one standard deviation. It shows that with five resources, the lead time continues to grow. However, figure 5-16 shows that by adding one resource, totaling six resources, the lead time stabilizes between six and eight days.

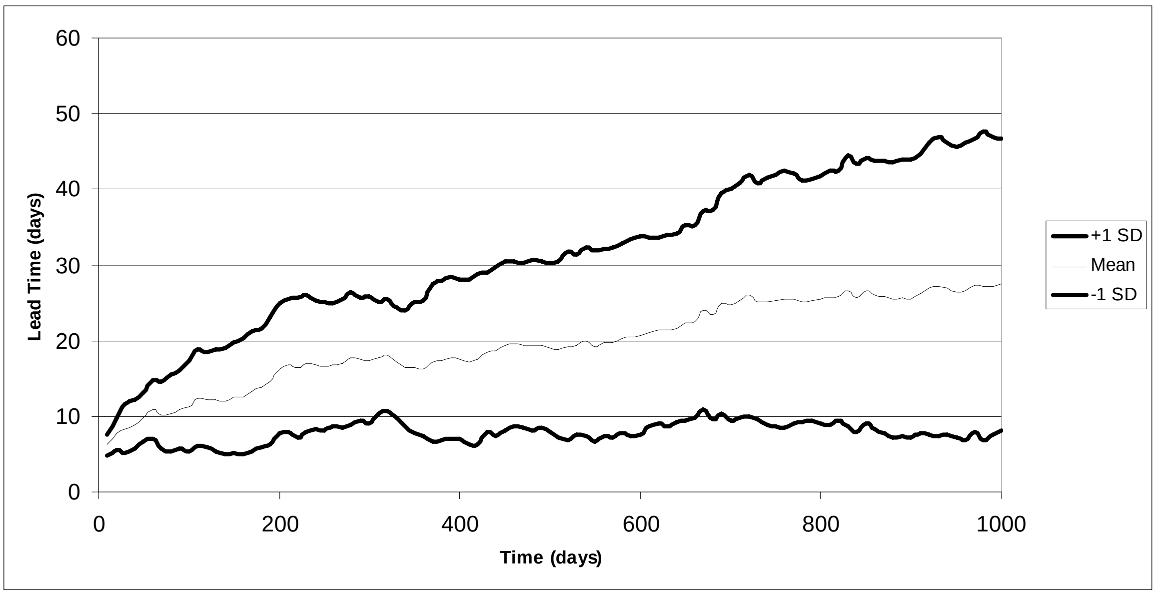



Figure 5-15 Lead Time (80% Rework, 5 Reviewers, Multiple Rework Cycles, 30 Iterations)

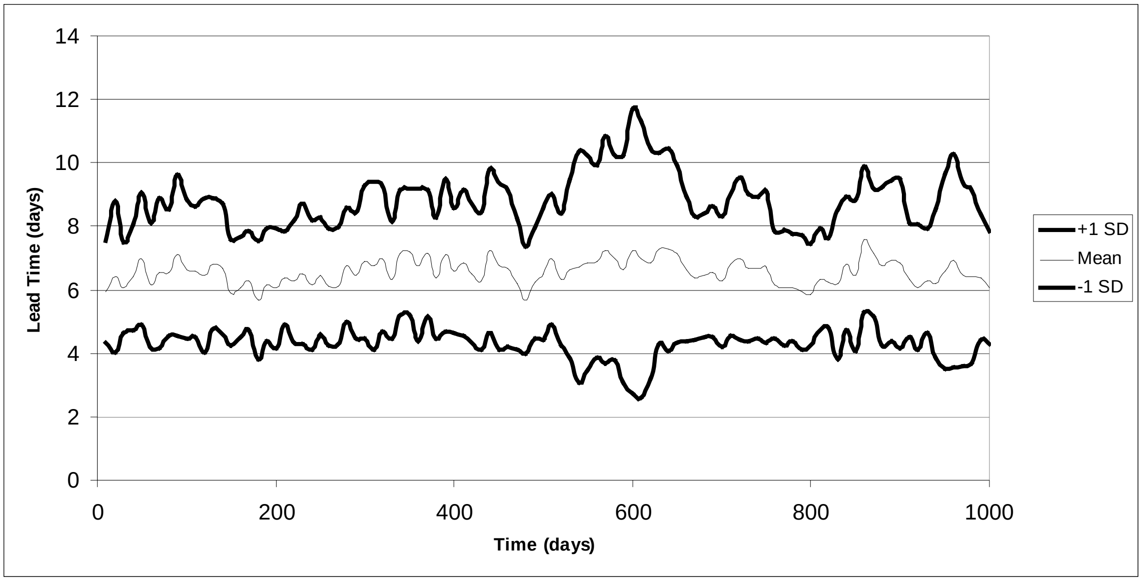



Figure 5-16 Lead Time (80% Rework, 6 Reviewers, Multiple Rework Cycles, 30 Iterations)

The production system illustrated in this chapter has three controllable throttles: (1) inflow of projects, (2) the number of review resources, and (3) the likelihood of rework. The first throttle of incoming projects is more difficult to control than the other two throttles. A major influence on the inflow of projects is political legislation. For example in California, legislation exists which requires healthcare facilities meet seismic upgrade requirements by 2030. To meet this requirement many hospitals have to be renovated or reconstructed which increases the number of projects submitted for state permits.

It is difficult to change legislation requiring stricter building codes because their requirements stem from failure situations. As mentioned in section 2.6, the role of OSHPD evolved over time. After a few healthcare facilities failed during seismic events, it was determined that the state government should play a larger role in regulating their design and construction.

On one hand the general public demands healthcare facilities remain open after a seismic event. On the other hand, the general public demands affordable healthcare. Therefore we must strike a balance between a technologically advanced healthcare facility and the cost to construct the facility. A facility can be constructed to meet higher seismic requirements; however, the cost to build that facility may make it infeasible. A complex situation arises between what the owner can expect to receive from providing a service and the funds they can allocate to construct those services. If this balance is not made, the facility may never be built or the healthcare provider will lose money.

It is also difficult to change legislation because it takes a long time to convince people a change is required. This is particularly true for legislation that deals with the safety of the general population. It is hard to convince a person that a healthcare provider should be given more time to upgrade their facilities to meet seismic requirements because the general population sees that as a cost of doing business in a state that experiences large seismic events. The majority of people in California accept that earthquakes happen and that an important buildings such as a healthcare facility need to remain operational after a seismic event. Therefore, legislation that would ease the seismic requirement for California healthcare providers would not be politically supported.

The second throttle on the system is the amount of resources the state permitting agency can dedicate to the review of incoming projects. The amount of resources available to any state review agency is limited, but knowing the limits on this resource is helpful to determine the impact when increasing review resources. However, it is possible for a state agency to reorganize the organization in a way to best utilize the available resources. For example, the review agency could provide training to industry engineers on the proper way to design and submit healthcare design projects. This upfront investment of time could improve the review process because the industry engineers would know the expectations of the reviewers.

The third throttle on the system is the likelihood of rework. This throttle can be controlled by providing higher quality drawings to the review agency. When this occurs the time to permit becomes more predictable for the owner and design team. If system performance is improved, who should pay for the added costs? In California, healthcare owners must pay for their projects to be reviewed. The cost is based on the total estimated construction cost. Once the review agency receives the funds, they decide how the funds will be expended. In their current system, the funds are spent to review the project in its entirety. However, it is possible to involve the review agency earlier. This early involvement process includes all the discipline engineers to eliminate errors that occur early in design. This entire review process becomes more complex as additional reviewers are added with different types of project sizes. This situation is explored in chapter 6.

# 6. CASE STUDY II: EFFECT OF ALTERNATIVE REVIEW ON WORKFLOW

## 6.1 Section Abstract

The purpose of the research presented here is to describe workflow through an organization that reviews submissions for building permit approval and understand the effect of an alternative review process on the time to permit assuming a certain level of staffing conducting the review. A 'normal' review process starts upon submission of a complete set of project drawings. The alternative review process that is considered here engages the state review agency early in reviewing the design with the owner, architect, engineer, and contractor.

I obtained data from a state permitting agency and developed a simulation model of an alternative review process to evaluate the disruption rework causes on the permitting approval process. This simulation model shows that incorporating the alternative review process considered can shorten the overall time to permit a healthcare facility. This alternative review process shifts the design and permitting curve, reducing the time to permit, while increasing the workload up-front. This research recognizes that such an alternative review process does not suit all projects, and that permitting agencies who adopt it must judiciously decide how to staff their organization to support process implementation.

This research uses data obtained from OSHPD to construct and test a current-state model of the organization. The model has been validated through in depth interviews with senior members of OSHPD. This research is limited to the California healthcare facility industry and to a data set acquired from OSHPD that contains data from July 2005 to July 2007 for all Facilities Development Division geographic regions. The findings are not compared to healthcare facility permitting agencies in other states and the adoption of the alternative review processes by OSHPD is outside the scope of this research.

A current state model of how healthcare facility projects "flow" through OSHPD for approval is developed using a portion of OSHPD's data. This model shows how plan review for permitting of a project flows through the architect, mechanical, electrical, structural and fire and life safety engineers. This current state model provides a foundation to study an alternative review process and its effect on workflow through OSHPD. This study does not simulate the construction and field review portion of the process. During the construction of a healthcare facility in California, government review is necessary to verify building codes are followed. The actions to accomplish this simulation are further elaborated on in the methodology section.

Modeling OSHPD processes reveals how rework affects the overall time to permit a healthcare facility design. For OSHPD, rework (or back checks as they are called within the industry), affects how long it takes a project to process through the plan review cycle. The research presented here shows a process that can improve the time to approve healthcare facility designs. Further framing of the organization and the boundaries of this research are presented in the next section.

## 6.2 Background and Scope

This research uses Lean production theory as a foundation to establish an alternative way of permitting healthcare facility designs. As mentioned in section 2.6, the OSHPD process is the focus of this section. I developed a computer simulation to model the time to permit drawings through OSHPD and I evaluated an alternative process to determine the reduction in permitting time.

## 6.3 Methodology

I used qualitative sampling by selecting OSHPD because it is the only state agency in California that permits healthcare facilities. In-depth interviews were conducted to understand how the current organization operates. I used quantitative methods to analyze existing operational data and then I developed a discrete event simulation model. This model allows us to understand changes in the existing system. I used in-depth interviews with members of OSHPD to qualitatively validate simulation findings.

I used discrete event simulation as the modeling engine. Discrete event simulations are well suited for this type of research because individual handoff events of information can be determined. An analytical model was not chosen because it is not well suited to process information that may not have similar units of measure. A numerical model was not chosen because distinct equations could not capture the dynamic nature of this research.

California healthcare facilities were chosen as a good example of how rework can affect the productivity of design and construction because they are complex facilities that require all engineering disciplines to participate in the process. Second, many stakeholders are involved with decision making during the course of facility development. Third, healthcare facility design and construction requires extensive government involvement to deliver the facility. These three parts are why healthcare facility construction is so complex and that the findings from this research are applicable to less complex construction projects.

## 6.4 What is Alternative Review?

An alternative form of review is to involve major stakeholders in facility procurement as early as possible in order to avoid the generation of non-code-compliant designs. A critical piece to accomplishing this process is for the team to acquire common understanding of the project scope, objectives, value proposition, etc. Common understanding stems from creating shared meanings through communication or collective experiences. Makela (2002) characterized common understanding as comprising of five elements: (1) shared ways of thinking, (2) shared ways of operating, (3) shared knowledge, (4) shared goals, and (5) trust.

On projects, common understanding occurs in two ways depending on project delivery (Lichtig 2008). In reference to facility construction projects, figure 6-1 represents traditional project delivery. Here the owner selects the architect early; they produce a concept or schematic design for the facility that is approved by the owner. Engineers are then hired to design the foundation, structural system, mechanical-, electrical- and fire, life, safety systems in the course design development. During this time, the common understanding of the facility increases among those involved in designing thus far. As this occurs, the owner brings on a construction management team or general contractor that will execute facility construction to get familiar with the design. Then, in the instance of healthcare facilities, once the design drawings are completed, they are submitted to FDD for review. During this time, major trade contractors may be hired to contribute to the creation of the contract documents. As this occurs the common understanding of the facility among project participants' approaches 100%.

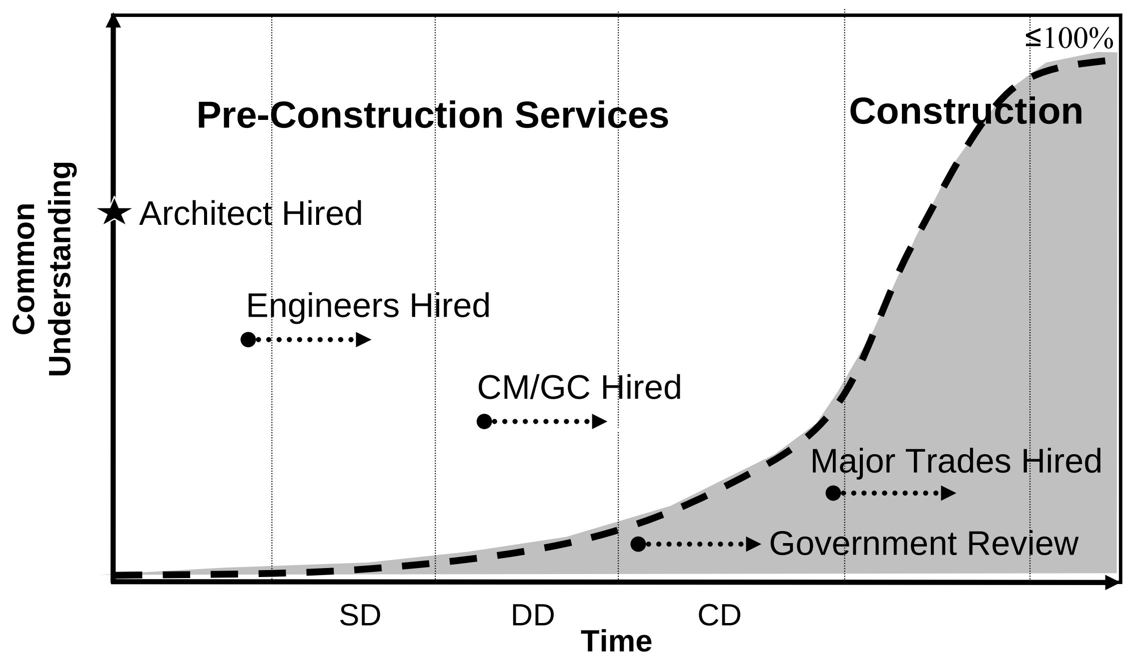



Figure 6-1 Level of Common Understanding Developed During Traditional Project Delivery (Modified from Lichtig 2008)

In contrast, figure 6-2 represents the integrated project delivery approach. Here the common understanding among project participants increases dramatically early on because the architect and construction manager or general contractor are hired early onto the project. In addition, engineers, major trade contractors, and government agencies are brought in early as well. This project delivery system has many benefits such as less rework, involvement of downstream players in upstream decisions, and better cost estimates; however, one major drawback is the level of effort is realized earlier in the system by many stakeholders and this puts additional cost pressures on the owner.

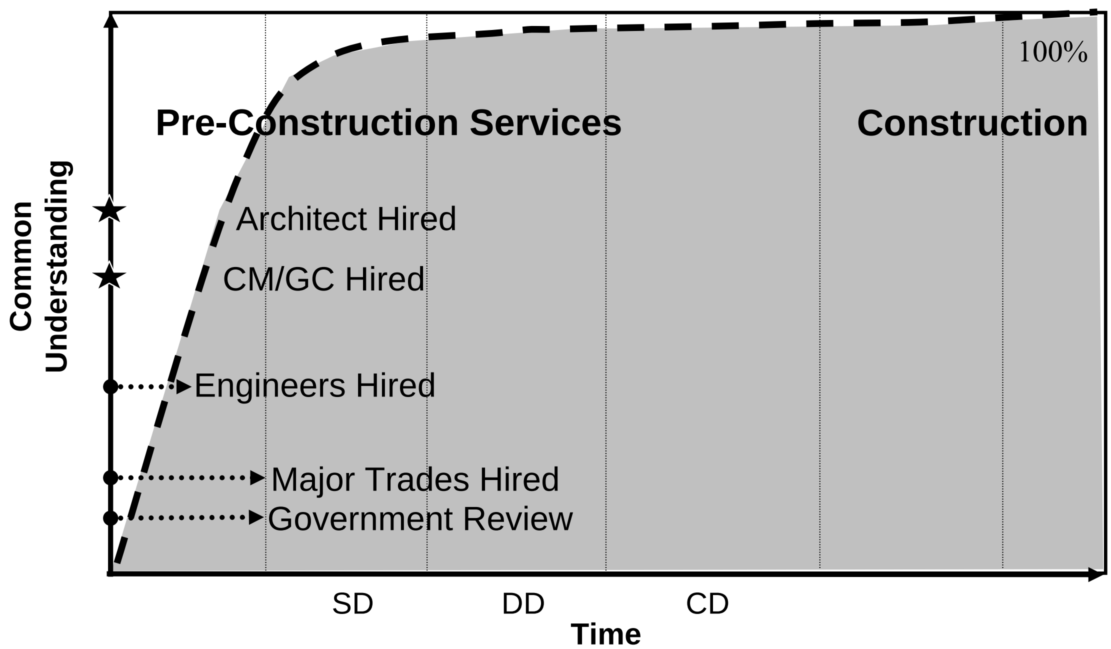



Figure 6-2 Level of Common Understanding Developed During Integrated Project Delivery (Modified from Lichtig 2008)

## 6.5 Shifting the Design Curve "Left"

Figure 6-3 shows the design and construction industry trying to shift the design effort to the left (curve no. 4) relative to where it is in more traditional project delivery (curve no. 3). To accomplish this shift, an integrated team must be put into place.

The American Institute of Architects' (AIA) guideline for design development breaks the design process into six project delivery stages that differ from the traditional stages, as shown on the x-axis of figure 6-3. The integrated delivery model, shown by curve no. 4 and the light grey text, on the x-axis shifts the effort to the left of the traditional curve. It also shows the government review process taking place much earlier in time.

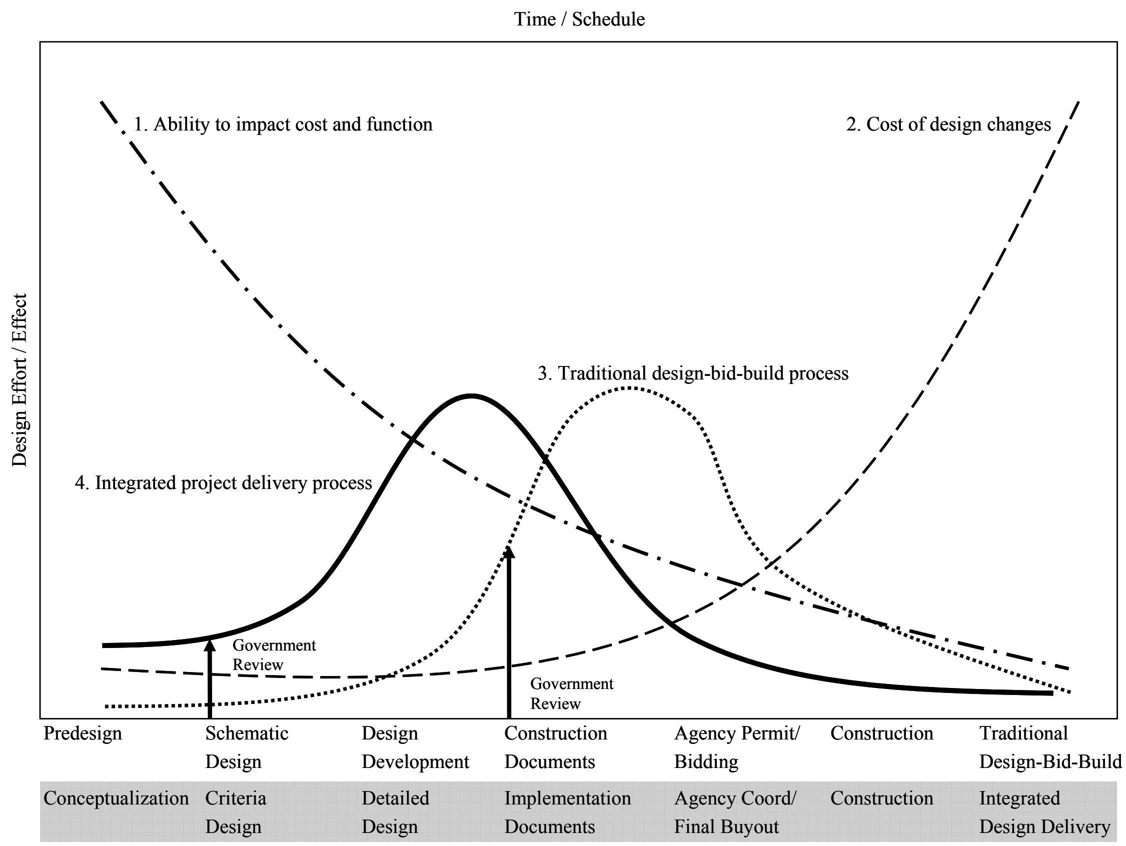


Figure 6-3 Shifting the Design Curve (Modified Figure 1 in Cook et al. 2007)

This shift left is accomplished through a different paradigm. According to Cook et al. (2007), the integrated project delivery approach "integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction." However, in integrated project delivery, the AIA does not offer many tools or advice on how to shift the design curve to the left. It highlights the need for collaboration, concurrent and multi-level designs, but falls short in suggesting specifics.

In contrast, this research, inline with the integrated form of agreement (IFOA), promotes the need for the Last Planner System™, reverse phase scheduling, target value design, built in quality, and work structuring. These techniques provide a basic framework for how owners, architects, designers, and contractors should interact with each other. The Last Planner System™ provides a framework to increase workflow predictability and provides simple to use metrics. Reverse phase scheduling provides a framework for working backwards from required milestones but more importantly to get all required stakeholders to buy into the schedule of deliverables and to understand handoffs between them. Target value design provides a framework to understand the costs involved with designing a facility. Built in quality provides a framework to develop processes that eliminate negative rework from facility design and construction. Work structuring provides a framework to think about how product and process fit together to ensure parts used in design are easily integrated into construction.

Table 6-1 shows the differences between traditional-, integrated-, and lean project delivery on various topics.

| Category | Traditional Project Delivery | Integrated Project Delivery | Lean Project Delivery |
|---|---|---|---|
| Teams | Fragmented, assembled on “just-as-needed” or “minimum-necessary” basis, strongly hierarchical, controlled | An integrated team entity composed key project stakeholders, assembled early in the process, open, collaborative | An integrated team, assembled early, openly share information and cooperatively collaborate |
| Process | Linear, distinct, segregated; knowledge gathered “just-as-needed”; information hoarded; silos of knowledge and expertise | Concurrent and multi-level; early contributions of knowledge and expertise; information openly shared; stakeholder trust and respect | Concurrent, multi-level and interdisciplinary; use of Last Planner System$^{TM}$, target value design, and built in quality, work structuring |
| Risk | Individually managed, transferred to the greatest extent possible | Collectively managed, appropriately shared | Collectively managed / shared allocation of contingency funds |
| Compensation & reward | Individually pursued; minimum effort for maximum return; (usually) first-cost based | Team success tied to project success; value-based | Team success tied to project success; value-based |
| Communications & technology | Paper-based, two-dimensional; analog | Digitally based, virtual; Building Information Modeling (BIM) (3, 4 and 5 dimensional) | Digitally based, virtual; BIM (3, 4 & 5 dimensional), core group development and decision matrix |
| Agreements | Encourage unilateral effort; allocate and transfer risk; no sharing | Encourage, foster, promote and support multi-lateral open sharing and collaboration; risk sharing | Require, encourage, foster, promote and support multi-lateral open sharing and collaboration; risk sharing |

Table 6-1 Traditional vs. Integrated vs. Lean Project Delivery (modified from Cook et al. 2007, Lichtig 2005)

How are the concepts of lean project delivery as described in table 6-1 implemented into an alternative review process? As previously mentioned, the FDD reviews design drawings in three ways: (1) '100%' contract drawings, (2) 'phased' and, (3) 'partial permits'. What is missing from these three processes is the early involvement of the plan reviewers to avoid the embedding of errors. These three processes place the plan reviewers in purely a reactive manner in which the plan checkers receive drawings and react by catching errors. This has created a culture where the government reviewers have become part of the quality control process. This is counter to the culture of lean where, the intent is to develop products without defects. On the one hand, an alternative review process allows the plan checkers to be interactive to call out concerns about the design while the process is actually occurring, which is a major reason the design curve can be shifted to the left. The government reviewers are not required to provide this input, however, understanding what the reviewers are going to look at and what errors they tend to catch is a requirement to develop designs without defects.

It is difficult to forecast how a change will affect an organization. Therefore, making a change in this organization takes time and it will take even more time to understand the results. Computer simulation is relatively inexpensive and can provide insight on the effect of change on the organization. This research utilized discrete event simulation to model the effect of an alternative review process.

## 6.6 Alternative Review Process

Through my discussion with personnel at all levels in the Facilities Development Division (FDD) I determined that two discrete event simulation models be developed to show how different permitting models can affect the throughput of healthcare facility permitting. The first model describes the current state of the organization and the collected data will be used to validate how the entire system behaves. This model will simulate the permitting process across the seven different geographical divisions that make up the FDD. The second model simulates the effect early involvement can have on the time to permit. Early involvement of the governmental plan reviewers (i.e., FDD's architects, electrical, mechanical, structural and fire, life, safety engineers) with the owner, architect, and design engineers can affect the delivery of healthcare facility permits. Synopses of the two models are shown in table 6-2.

| **Model Type** | **FDD Review** |
|---|---|
| Current state | Final contract drawings reviewed by FDD |
| Early involvement | Input given on initial assumptions |

Table 6-2 Proposed Discrete-Event Simulation Models for OSHPD

This alternative review process differs in at least five ways from existing OSHPD practice. The first difference is the idea of zero quality control which eliminates embedded errors early on in the design process by all process stakeholders, to include FDD personnel, owners, architects, and designers. The second is to involve the structural reviewers in the siting, blocking and stacking, and fire, life, and safety phases of the design which occur very early on. The third difference is the involvement of geotechnical engineers with the design criteria. The fourth is a schedule for design submittals with defined deliverables and times. The fifth is the ideal of a deal breaker. A deal breaker is a term used for a project that does not fulfill its promise to the owner and design team. These differences can occur because the process involves major stakeholders as early as possible in project delivery in order to accomplish zero quality checks in the design. This alternative review process reduces downstream rework.

## 6.7 Alternative Review Discrete Event Simulation Model

### 6.7.1 Model Objectives

The simulation was created to illustrate the concept of an alternative review process of reviewing and permitting drawings. By creating this simulation, I wanted to understand the impact of an alternative review process on rework and permitting time. Finally, as the purpose for all models, I wanted to utilize discrete event simulation for organization decision making. Two specific questions are posed for this computer simulation. The first is should we use an alternative review process? If the answer is yes then how much time can an alternative review process save?

### 6.7.2 Model Assumptions

Four assumptions were used in developing the computer simulation. The first is the model developed represents one out of seven plan review regions. All of the plan review regions have the same organizational layout for how drawings are approved and permitted within OSHPD. The second is the assumption that all plan reviewers are fully trained. This was made, because the majority of the personnel that work at the organization are long time employees of OSHPD. The third assumption is reworked items have a higher priority than items that have not been reviewed yet. This assumption was made because that is how the regions process their workflow. Finally, it was assumed that projects can be reworked indefinitely, which is supported by interviews from OSHPD personnel.

### 6.7.3 Model Description

Figure 6-4 shows a simple discrete event simulation model that illustrates the review process for healthcare facility design in California. One part of the model, highlighted and noted with the number '1' shows the first review process. Drawings are located in the Drawing Table queue. Review personnel are categorized into five disciplines representing the (1) Architect, (2) Structural Engineer, (3) Mechanical Engineer, (4) Electrical Engineer, and (5) Fire, Life, and Safety Engineer. Each personnel queue contains one individual.

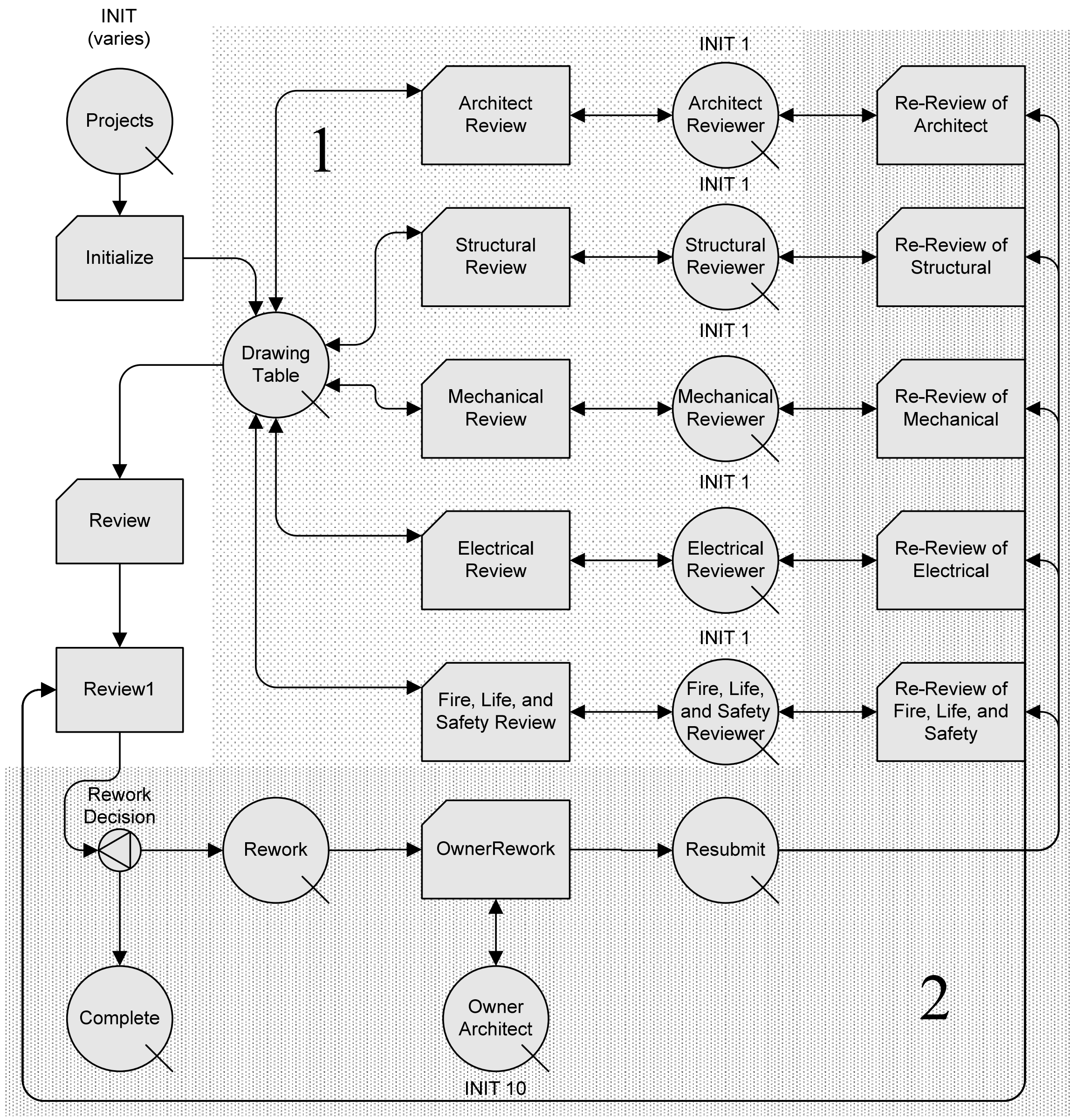



Figure 6-4 Discrete-Event Simulation of Current and Alternative review process (Model 1)

The personnel queues are associated with discipline review activities. The review activity times are normally distributed and depend on project size; larger projects have larger review times. The process of calculating the review times are discussed in section 6.9.6. Project categories, cost range and review strategy are shown in table 6-3.

| Category | Project Cost Range | Review Strategy |
|---|---|---|
| I | Less than $50K | Traditional Plan Review |
| II | Between $50K and $1M | Traditional Plan Review |
| III | Between $1M and $10M | Traditional Plan Review |
| IV | Greater than $10M | Traditional Plan Review / Partial Plan Review |

Table 6-3 Project Categories and Review Strategy

Projects enter the system in random order and are reviewed following a first in first out (FIFO) scheme. Each project must be reviewed five times, one for each review discipline and once completed, the project flows into the second part of the simulation model.

The second part of the model highlighted and noted with the number '2' shows a dynamic rework cycle. The first part of this cycle is to determine if rework is required. Each project size has a different chance of being subjected to rework. The process of calculating rework rates are discussed in section 6.9.5. If the project does require rework it is placed in the rework queue; otherwise it is placed into the complete queue.

Upon entering the rework queue, the simulation engine randomly determines which discipline will require re-review. This information is tracked for each individual project. The project then goes into the owner rework activity. This simulates the drawings going back to the design team to correct errors. The owner rework time is category specific. Larger projects require more owner rework time while smaller projects require less. The duration of owner rework is sampled from a normal distribution.

Upon owner rework completion, the project flows into the resubmit queue awaiting re-review by the previously determined discipline. The simulation matches the assigned error with the correct discipline and then draws the appropriate reviewer into the re-review activity. Upon re-review completion the project re-enters the rework decision fork again. A project requiring re-review has a higher priority than a first review continuing first in first out, so that projects that have been in the system longer are completed earlier.

The rework cycle continues until the project is determined to not require rework, and thus gets approved. The chance of rework decreases with each rework cycle simulating the improvement of design drawings which is also modeled by Gil (2003).

The means and standard deviations acquired from data collected by OSHPD. I categorized projects into five categories that represent how OSHPD tracks their projects. In addition, each project carries a characteristic that determines whether or not it was reviewed using an alternative review process. Finally, the characterized resource carries with it saved properties to include how many times it was reviewed and reworked.

Figure 6-5 represents a variation of the review process utilizing a dedicated rework team. This model increases personnel resources and allows the first review of projects to continue uninterrupted because rework is handled by another set of review personnel. One theory utilized within lean production theory is to have one team continue with production and all subsequent rework is handled by another team. This allows the production team to continue uninterrupted. One example in construction occurs with duct work installation. One team is dedicated to duct work installation and is not required to perform rework. Then, if rework is required, another team is assigned to accomplish the rework tasks. Uninterrupted workflow increases productivity because the installation team does not have to breakdown work areas and reset them up to conduct rework in parts of the facility that have been completed. This duct work installation process increases productivity, decreases setup times and increases in motivation. Setup times are decreased because a substantial amount of transportation and installation of scaffolding is required for ductwork. Once setup, it is difficult to take down and slows down production. Increased motivation occurs, because the workers can see their progress and feel that more is being accomplished. Workers are de-motivated by negative rework. If negative rework exists that must be addressed, a separate team that is not familiar with the work of the first team is then used to correct negative rework. This rework team can then see the work in front of them as another production line. However, following this duct work installation process may not provide the appropriate level of continuity to the rework team. They may not know what deviations may have been completed by the installation team.

In the plan review scenario the benefits of the process is increased productivity. Increased productivity occurs because a review team concentrates on looking at all of the drawings to complete the first review. Subsequent changes to drawings are then only reviewed by the rework team. The downside to this process, like the one mentioned earlier is the continuity of the information. For example, the rework team may not be familiar or understand what changes are needed to the drawings.

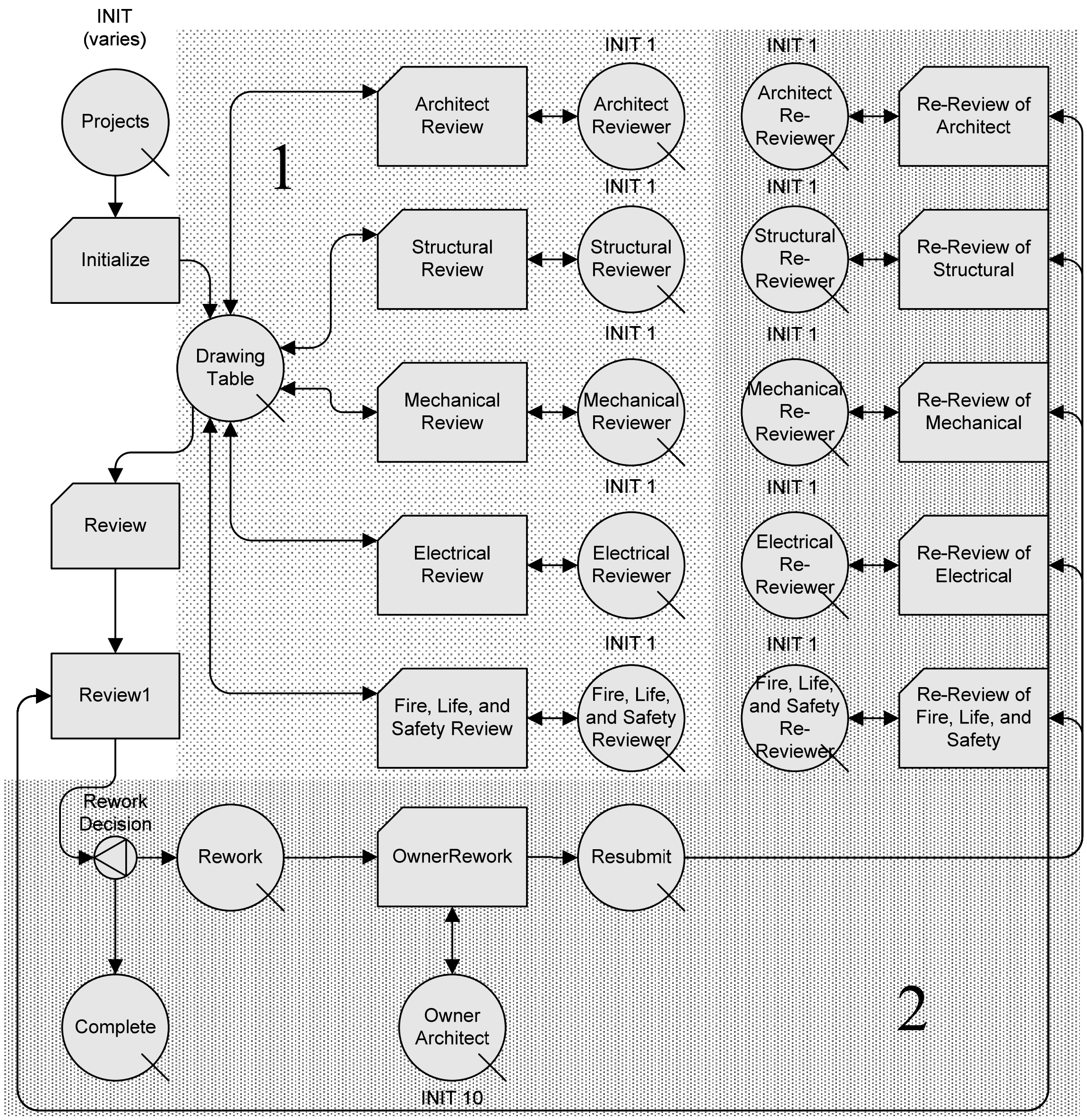



Figure 6-5 Discrete-Event Simulation of Current and Alternative Review Process

Utilizing a Dedicated Rework Team (Model 2)

## 6.8 Methods

The following methods were used to develop and understand the presented discrete event simulation models:

1. Database analysis

2. Resampling
3. Discrete event simulation programming engine
4. Computer model output analysis

### 6.8.1 Database Analysis

The database obtained from the FDD had been constructed using Microsoft Structured Query Language (SQL). The database contained over 100,000 points of information and was linked by five primary tables. This database was exported into Microsoft Access and analyzed using queries. Multiple queries were developed to determine mean times of review and re-review, the number and size of project categories and the rate of rework occurrences. Further description of the analysis is found in section 6.9.6.

### 6.8.2 Discrete Event Simulation

STROBOSCOPE is the computer language used to develop the discrete event simulation model of FDD current and future review processes. The computer language was tailored and written to accommodate a number of processing realities. More specifics on the use of the computer language are in section 6.9. The models' computer code is located in appendix C.

### 6.8.3 Computer Model Output Analysis

Data obtained from the simulation model was imported into Microsoft Excel to build a text file that was used to run resampling statistics using a free educational software called R. R output is used to construct normal distributions of mean time to permit, standard deviations, and instances of rework occurrences. This information was used to analyze the changes to the mean time to permit using different input scenarios and stability of the system due to those changes.

### 6.8.4 Resampling

Resampling generates additional data points using simulation. Two types of resampling exist; (1) jackknife and (2) bootstrapping. Jackknife uses subsets of available data to obtain sample statistics. Bootstrapping samples from a data set with replacement and then creates sample statistics from the new data sets. Bootstrapping is the technique employed in this research to create first review and re-review activity times within the discrete event simulation. The technique is used to determine the mean time to permit for the sensitivity analysis simulation scenarios.

## 6.9 Calibrating the Model

Calibrating a simulation model to real-world data is essential. This ensures that changes to simulation inputs will provide realistic system behavior. The discrete event simulation model was calibrated to existing data in seven steps:

1. Loading the system
2. The rework decision
3. Assigning rework
4. Matching problem
5. The rework rate
6. Determining the review times

7. Time to permit

These seven steps are used to calibrate the time to permit

### 6.9.1 Loading the System

Loading the system with projects must emulate how the organization deals with different types of work. Since not all work is the same and work can come into the system at different times it was important to allow for this randomness of when projects are received by the organization. In the model the amount of projects must be initially defined.

The code initializes the system with 10 projects for categories I - IV. By default, the projects will enter the system in a first in first out fashion. This means that all category I projects will be worked on first, all category II projects next, all category III projects next, and finally all category IV projects last. This default was changed to randomize how projects enter the system by assigning random numbers to each project. The projects are then sorted according to this randomly assigned number.

### 6.9.2 The Rework Decision

Whether or not a project requires rework is decided dynamically within the simulation model. As a project completes its first review it enters the rework decision fork. A characteristic *r* assigned for each project category represents the percent chance that the project will require rework. Table 6-4 shows the likelihood of rework for each of the categories.

| Category | Likelihood of Rework (%) |
|---|---|
| I | 90 |
| II | 99 |
| III | 93 |
| IV | 88 |
| IV using PPR | Varies |

Table 6-4 Category of Projects

Table 6-4 shows that a majority of projects that enter the system require rework. This high percentage of rework was qualitatively confirmed through conversations with senior members of the FDD. Category IV using PPR varies because this value is changed for the sensitivity analysis.

The rework decision contains a provision that reduces the chance of rework each time the project is reworked. This reflects the assumption that as the project is reworked, the quality of design drawings improves and has a lesser chance of needing rework. This is shown in the partial code below.

*STRENGTH RD3 100-Review1.DrawingSet.r/Review1.DrawingSet.ReworkFactor;*

*STRENGTH RD4 'Review1.DrawingSet.r/Review1.DrawingSet.ReworkFactor';*

This code dynamically assigns the strength of each link flowing out of the Rework Decision Fork. As projects flow into the Rework Decision each project is evaluated using the *r* characteristic. In addition a Rework Factor is initiated to the value of 1. On the first pass the project enters Rework Decision, the *r* characteristic is pulled into the equation and divided by the ReworkFactor. If a category I project is being cursored then the percent chance of rework will be 90, 90 divided by 1. If it is determined that the project will require rework it will flow through the rest of the rework queues and activities.

Once the project is re-reviewed by one of the disciplines it is released back into the rework decision loop. Upon being released, the ReworkFactor is increased by one. When the project is reevaluated in ReworkDecision, the percent chance that it will require rework is now 45, 90 divided by 2. If rework is again required, once the re-review is completed the chance of rework is now 30, 90 divided by 3. This dynamic rework cycle can occur indefinitely however this is rare. During simulations, projects reworked more than four or five times is rare.

This rework loop was then tested to ensure it follows the intended purpose. To test this scenario five category I projects were loaded into the system and the *r* (rework) characteristic was set to 100, representing a 100% chance on the first pass that the project will require rework. Therefore, all projects will require at least one loop of rework. Figure 6-6 shows the likelihood of rework versus the number of rework iterations. On the second pass the likelihood of rework is 50%, on the third pass the likelihood is 33%.

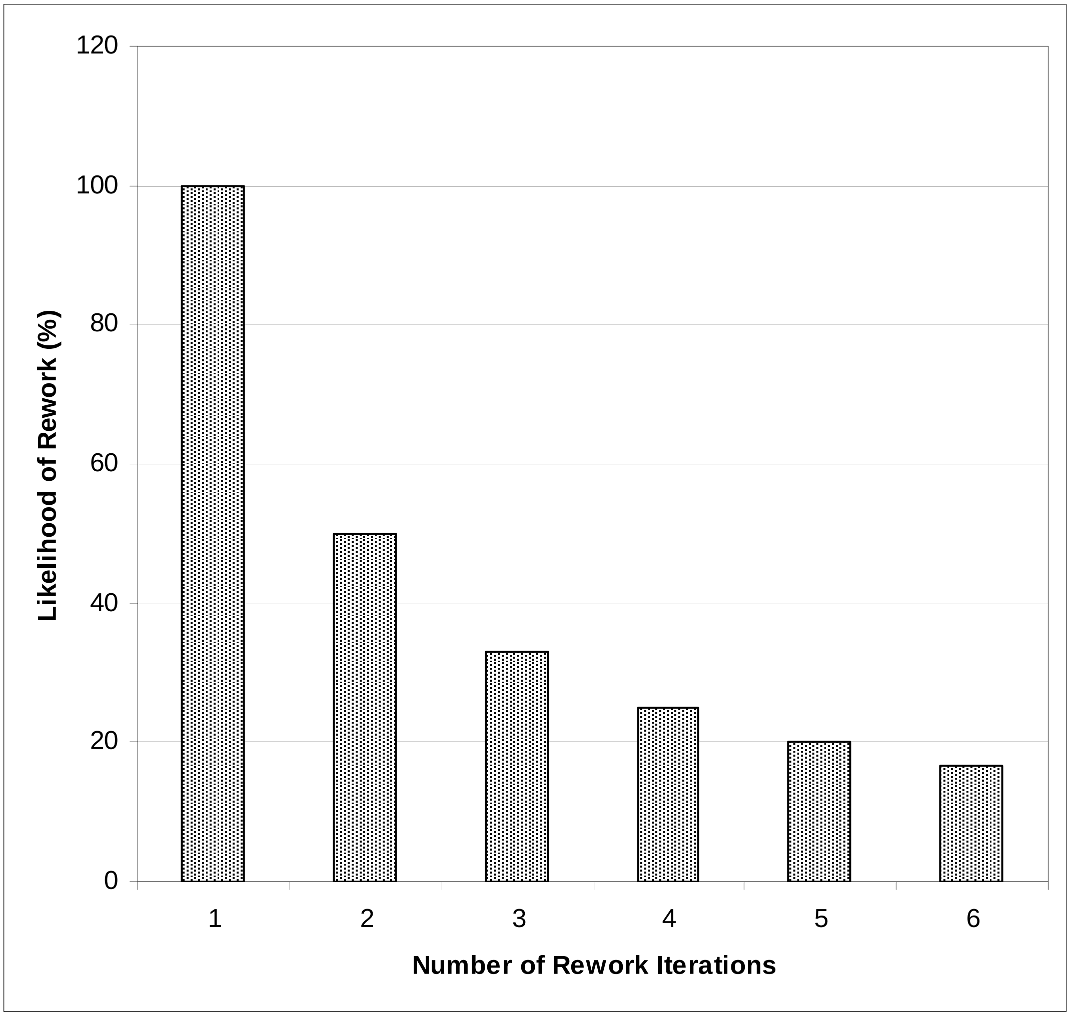



Figure 6-6 Likelihood of Rework vs. Number of Rework Iterations

Table 6-5 and figure 6-7 show the rework rates used in the computer simulation. The algorithm used to calculate the rework rate works by taking the first review percentage and dividing it by the current rework cycle. For example in category IV, the percentage chance of rework is 90%.

| Category | Review | Rework Rate |
|---|---|---|
| I | 1st | 84% |
| | 2nd | 42% |
| | 3rd | 28% |
| | 4th | 21% |
| II | 1st | 88% |
| | 2nd | 44% |
| | 3rd | 29% |
| | 4th | 22% |
| III | 1st | 94% |
| | 2nd | 47% |
| | 3rd | 31% |
| | 4th | 24% |
| IV | 1st | 90% |
| | 2nd | 45% |
| | 3rd | 30% |
| | 4th | 22% |

Table 6-5 Data for Rework Rate (Simulated)

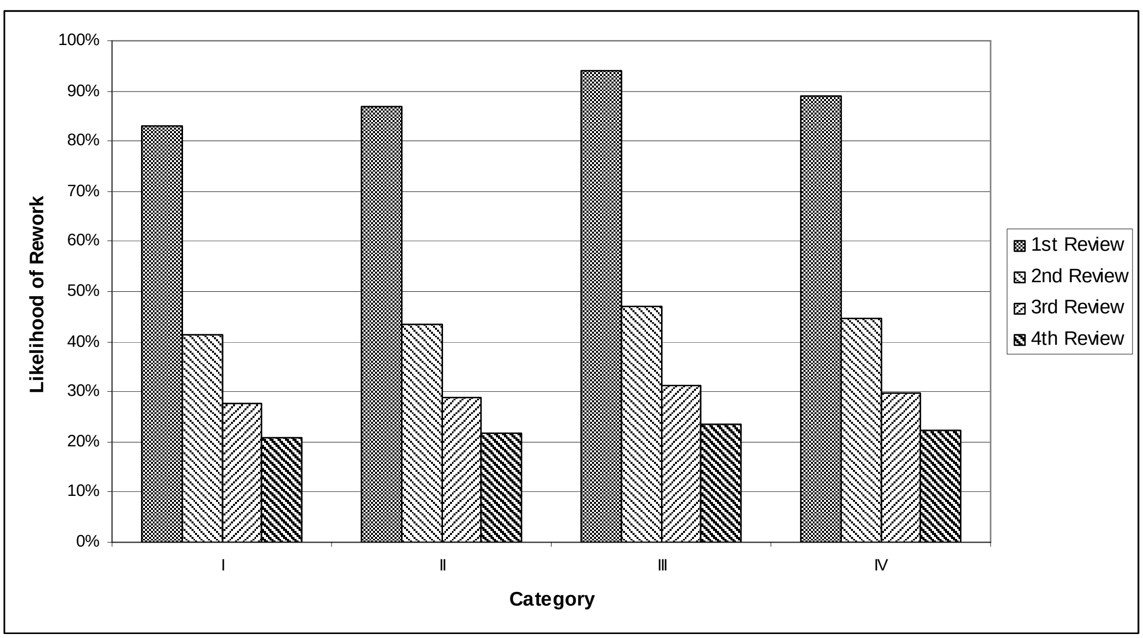



Figure 6-7 Likelihood of Rework per Category (Simulated)

### 6.9.3 Assigning Rework

As an error is discovered in the review process it has to be assigned to a specific discipline. This error is associated with a certain discipline whether it be architect, structural, mechanical, electrical or fire, life, and safety rework. For example, a rework cycle may be triggered by the fire, life, and safety reviewer finding an error in the layout of the exiting plan for the healthcare facility which requires the sprinkler locations be changed. Corrected errors are then resubmitted for review. Upon the second review, a mechanical error was detected in which the size of the pipe supporting the change in fire sprinkler location is not adequate and then needs to be corrected. The design team again corrects the issue and sends it back for review. Upon the third review, another error is detected, the new fire sprinkler locations do not coincide with the proper skin of the material and has to be reworked. Finally, the design team corrects all deficiencies and the project is reviewed with no further errors and is completed on day 283. Note: in this simulation, project 20 was first reviewed on day 10 resulting in an overall time to permit of 273 days.

One limitation of the simulation is that the project could have multiple errors after the first review. The model does not account for this situation, however the project is allowed to be reworked more than once.

### 6.9.4 Matching Problem

As mentioned in the previous section the error is randomly assigned to a discipline. As the project flows through the Resubmit queue the error assigned to the project is matched up to the correct review discipline through the following code fragments.

### 6.9.5 Determining the Rework Rate

I analyzed the OSHPD logbook data to extract the rework rate and calculated the number of rework cycles category I to IV. Figure 6-7 shows the different states that a project can be in for the two year period of data analysis. Multiple scenarios exist where a project is considered approved. In these scenarios, all projects are considered approved with the following results. Two projects approved with no rework cycles, two approved with one rework cycle, two approved with two rework cycles, and three approved with three rework cycles. I realize that this process could produce inaccurate rework rates from existing data, however, senior members of the FDD confirmed that the rework rates were accurate.

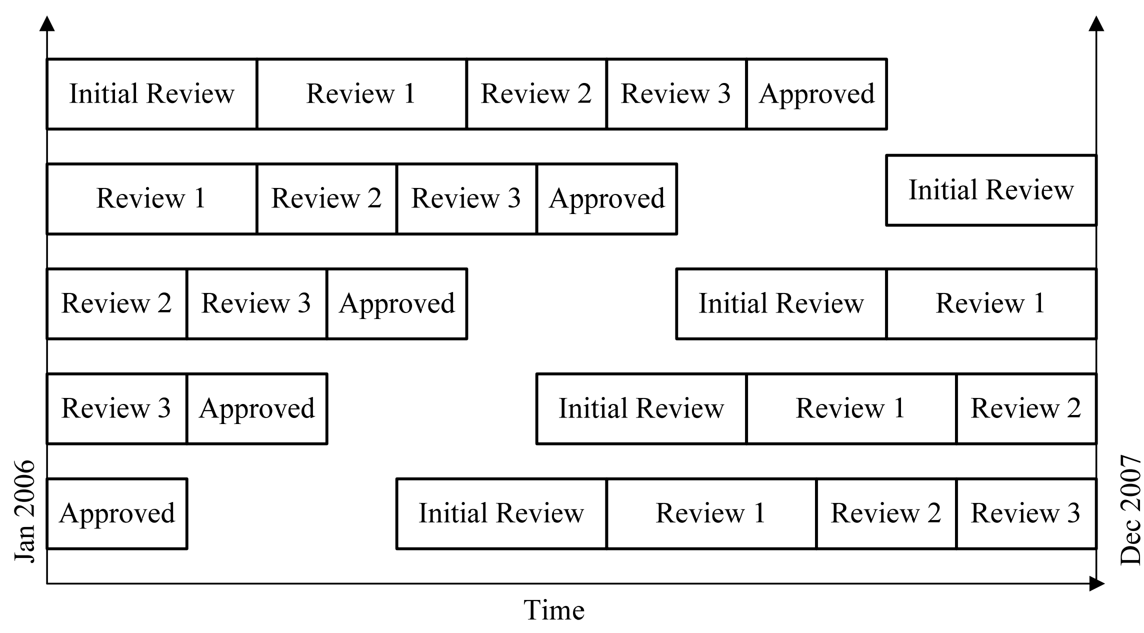



Figure 6-7 Project Review Scenarios

Table 6-6 shows the category rework rates for first, second, third and fourth reviews.

| Category | No. of Projects | Review | Rework Rate |
|---|---|---|---|
| I | 763 | 1st | 83% |
| | | 2nd | 42% |
| | | 3rd | 9% |
| | | 4th | 2% |
| II | 1225 | 1st | 87% |
| | | 2nd | 42% |
| | | 3rd | 13% |
| | | 4th | 3% |
| III | 235 | 1st | 94% |
| | | 2nd | 50% |
| | | 3rd | 16% |
| | | 4th | 2% |
| IV | 73 | 1st | 89% |
| | | 2nd | 52% |
| | | 3rd | 26% |
| | | 4th | 7% |

Table 6-6 Data for Rework Rate

In table 6-6, column one shows the category and the number of projects evaluated from the OSHPD database. For example, in category I, 763 projects were evaluated. After the first review 83% required rework. 42% of the projects require rework after the second review. 9% of the projects require rework after the third review and only 2% of the projects require more than four rework cycles. Figure 6-8 is a graphical representation of the data calculated from the OSHPD database.

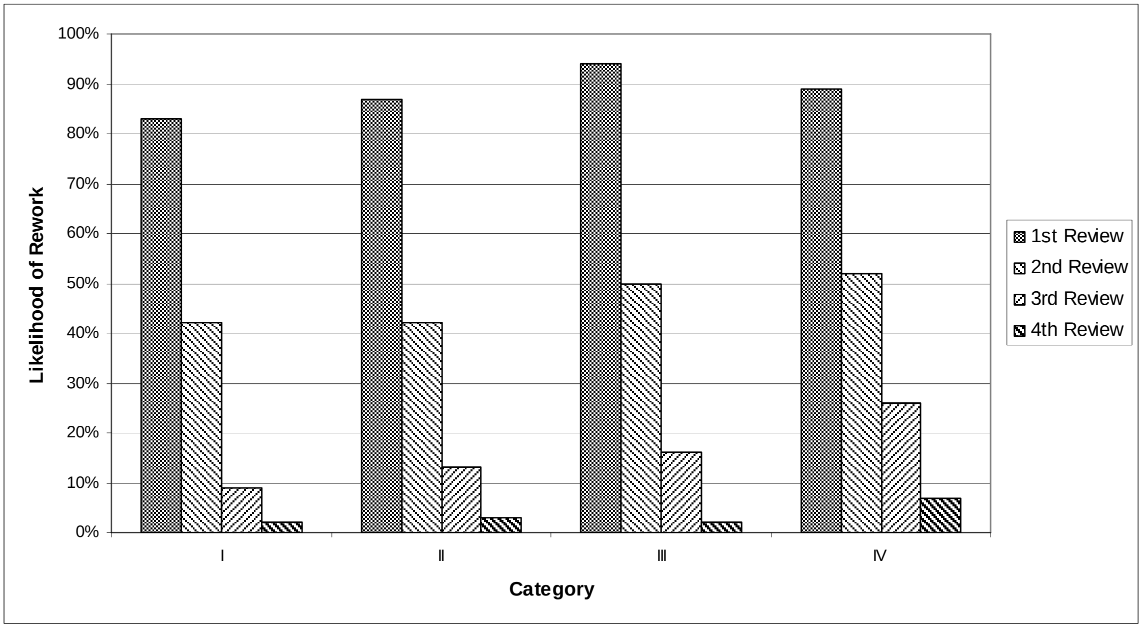



Figure 6-8 Likelihood of Rework per Category

In all four categories, the rework rate for the first review is above 80% and then declines. In most instances, the rework rate for the second review is approximately half the rework rate for the first review. The rework rate continues to decline for the third and fourth reviews. This also shows that very few projects get approved on their first review and in many instances the project is reworked multiple times. The information provided in table 13 and figure 6-9 represent calculated data from the OSHPD logbook database.

6.9.6 Determining Review Times

This organization collects and places all of its data entry into a large database. The data obtained tracks over six years of workflow through the organization. An Access database obtained from OSHPD dated 15 June 2007 was used to extract activity durations that were used in the discrete event simulation model. This database contains five different tables (1) Counties, (2) Facility, (3) Projects, (4) Reviews, and (5) RvwAct (Review

Activity). Figure 6-9 shows the five tables in the Logbook Access database and their relationships to each other and is read from left to right. The data in the Counties Table is linked to the Facility table through the CountyID key. The Facility table is linked to the Projects table through the Facno key which is the facility number. Each California healthcare facility (existing and proposed) receives a unique identifier. The Projects table is linked to the Reviews table through two fields the ProjNum (Project Number) and SubNum (Submission Number). Each new project entered into the FDD system is given a unique identifier for tracking purposes. The Reviews table is linked to the RvwAct (Review Activity) through the ACT field. The ACT field represents the activity code (a type of review) that was conducted on the project.

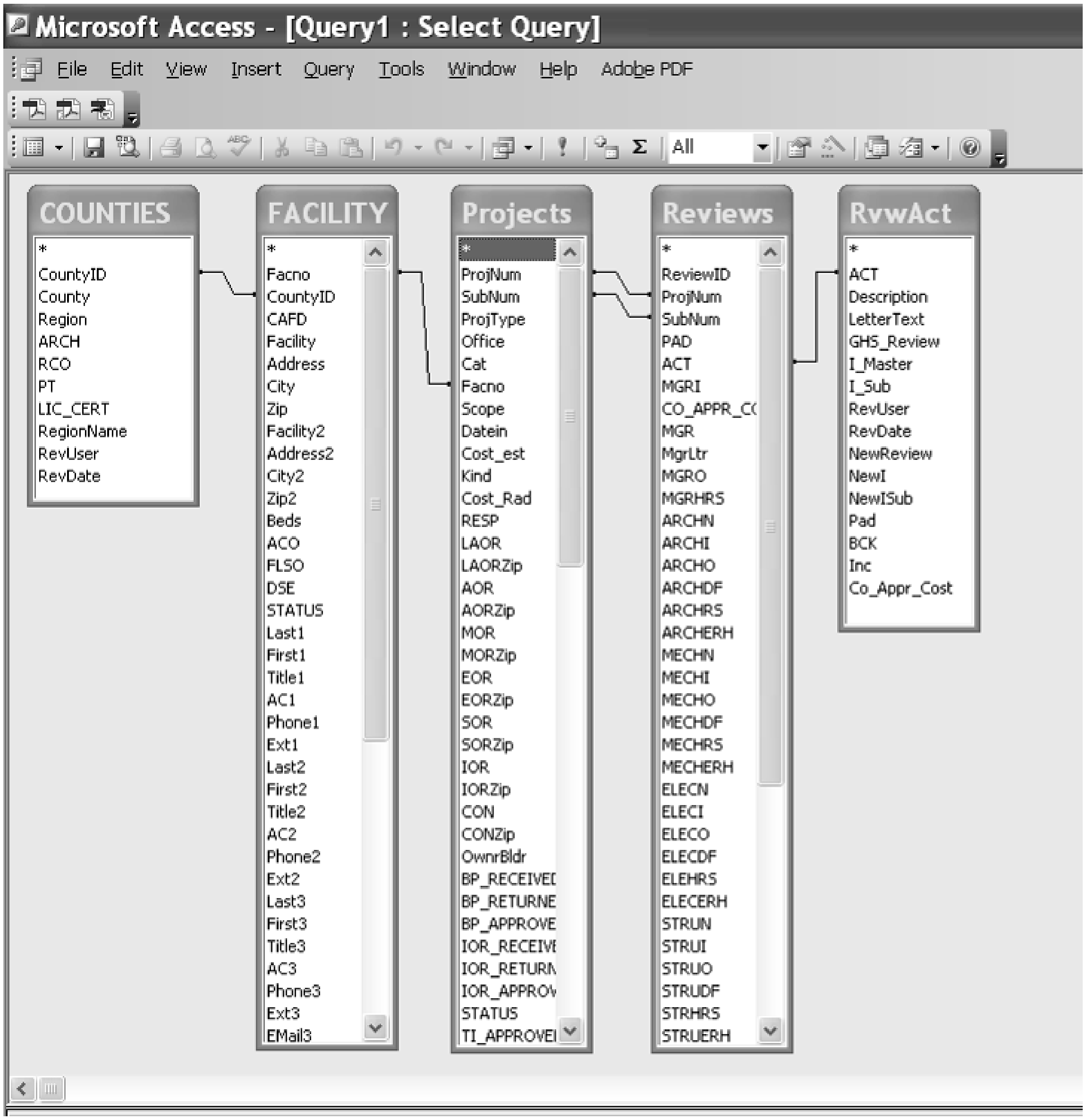



Figure 6-9 Logbook Access Database Relationships

Figure 6-10 shows queries from the database that were constructed from two tables (Projects and Reviews). In this example, projects were filtered to show (1) a construction cost of less than $50K (2) have ACT review codes of either 33* or 34*, and (3) be logged in to the system between 1 January 2006 and 31 December 2007. The 33* series numbers represent the first review of the project while the 34* series numbers represent any subsequent backchecks or rework of the project documents. The criteria

33* and 34* filters all projects with 331, 332, 333….349. A backcheck is any defined defect where the project had to be returned to the design team for correction of errors.

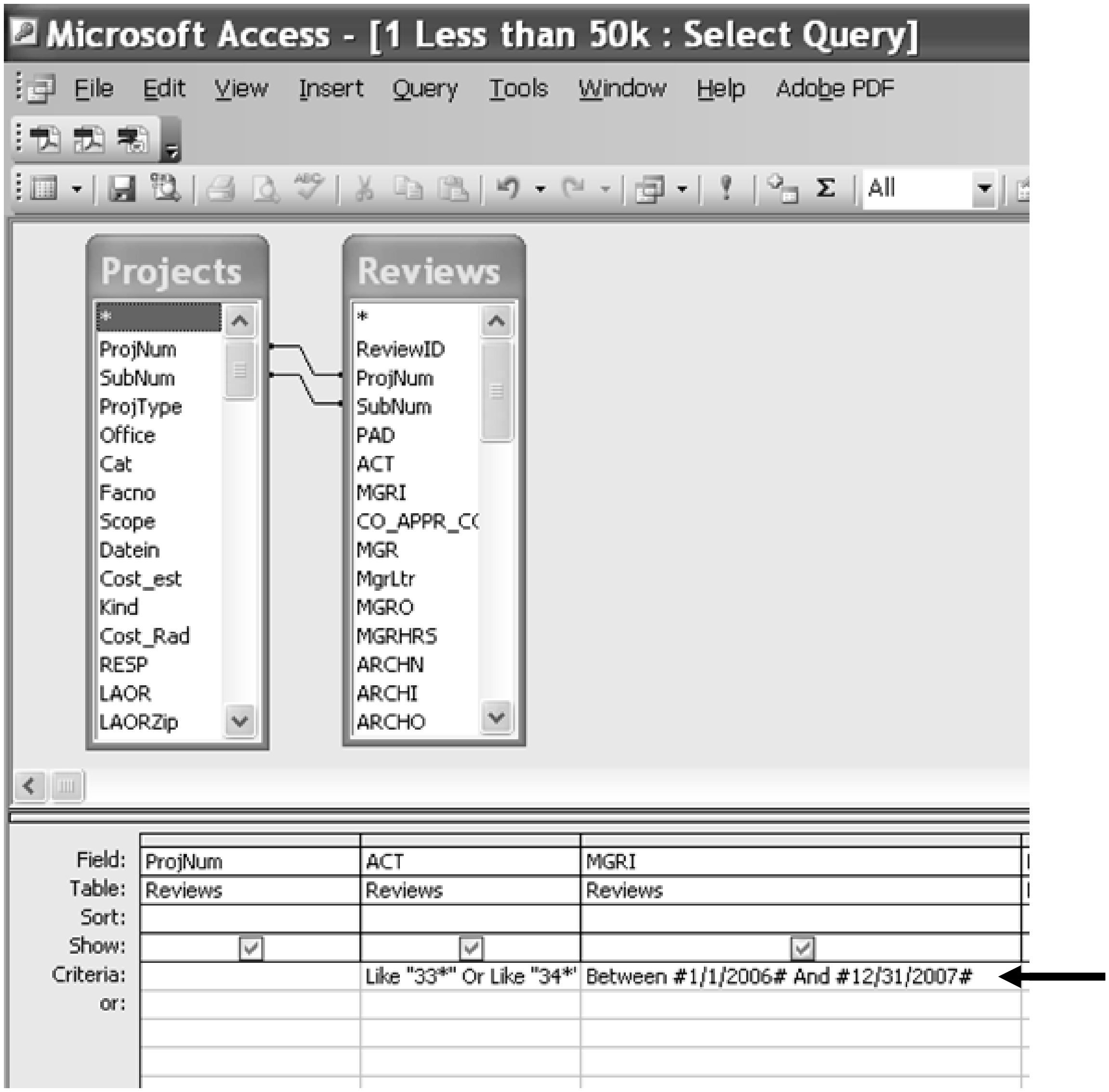
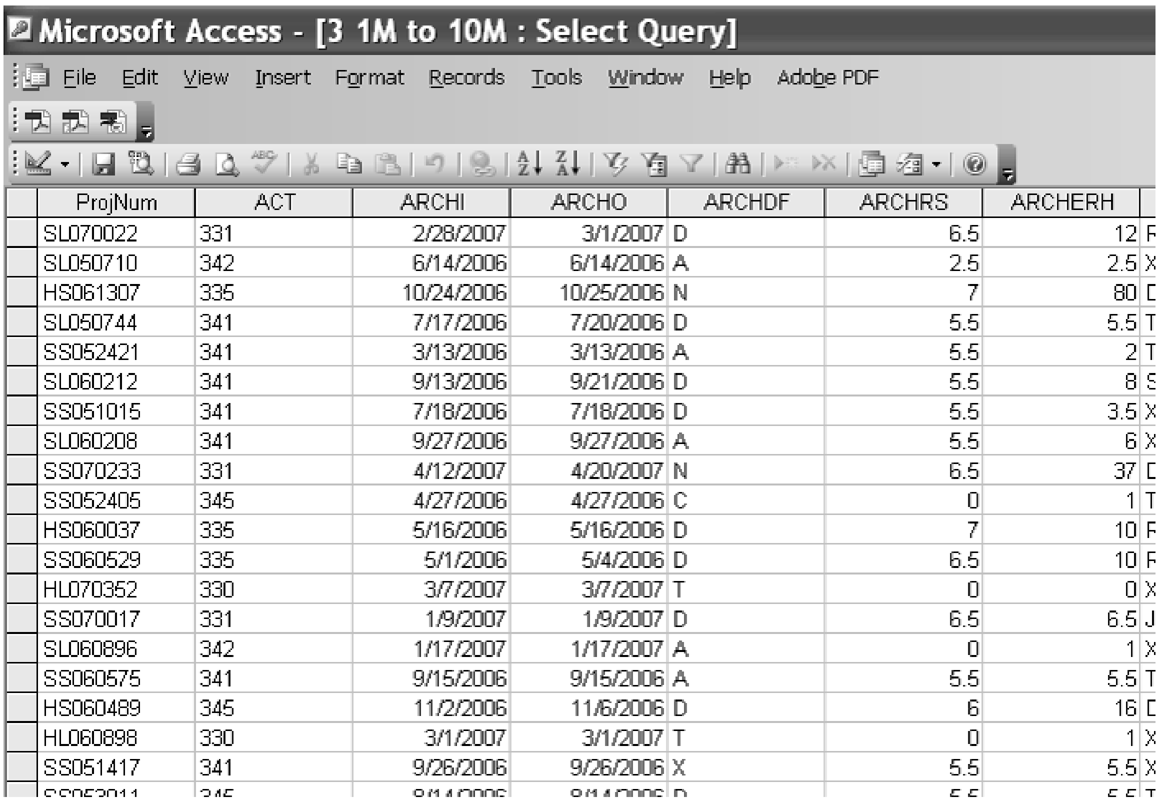



Figure 6-10 Example of the Query Constructed from Logbook

Figure 6-11 shows a query for projects that cost more than $1M and less than or equal to $10M. The first column represents the unique project number associated with the project. The second column is the activity, for example the first row shows an ACT of 331 which stands for the first review. The third column ARCHI shows when the architect took in the project which was 28 February 2007, the fourth was then logged out on 1

March 2007. The fifth column ARCHDF shows the letter D which means the reviewer defected the drawing; therefore, this drawing set would have been returned to the design team for corrections. ARCHRS represents the total hours to review the drawings, 6.5 hours. ARCHERH represents the hours estimated to review, 12 hours. This information was then exported to Excel and sorted so that all the 33* activity codes would be together and the 34* codes would be together.

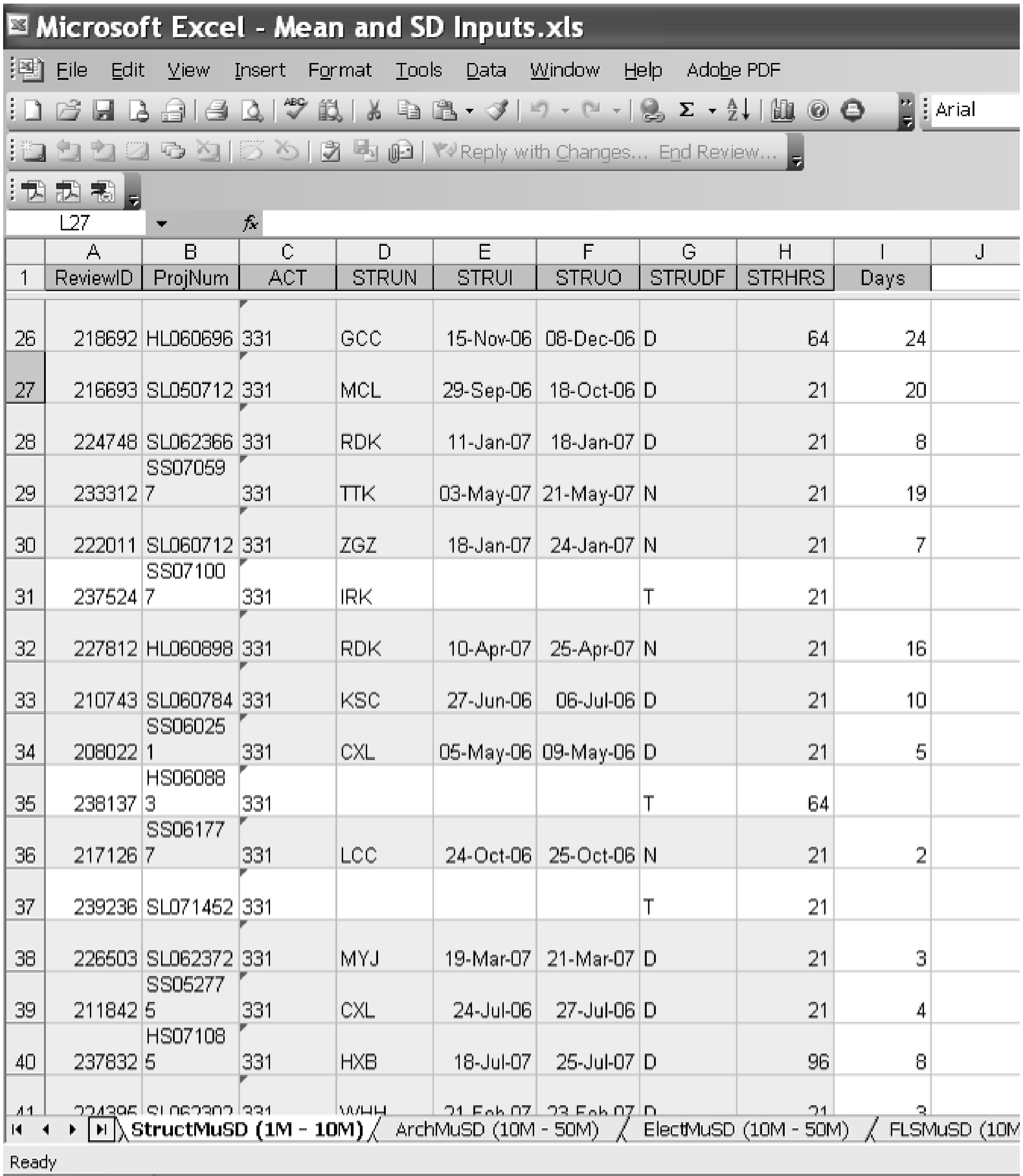



| ProjNum | ACT | ARCHI | ARCHO | ARCHDF | ARCHRS | ARCHERH | |
|---|---|---|---|---|---|---|---|
| SL070022 | 331 | 2/28/2007 | 3/1/2007 | D | 6.5 | 12 | F |
| SL050710 | 342 | 6/14/2006 | 6/14/2006 | A | 2.5 | 2.5 | X |
| HS061307 | 335 | 10/24/2006 | 10/25/2006 | N | 7 | 80 | D |
| SL050744 | 341 | 7/17/2006 | 7/20/2006 | D | 5.5 | 5.5 | T |
| SS052421 | 341 | 3/13/2006 | 3/13/2006 | A | 5.5 | 2 | T |
| SL060212 | 341 | 9/13/2006 | 9/21/2006 | D | 5.5 | 8 | S |
| SS051015 | 341 | 7/18/2006 | 7/18/2006 | D | 5.5 | 3.5 | X |
| SL060208 | 341 | 9/27/2006 | 9/27/2006 | A | 5.5 | 6 | X |
| SS070233 | 331 | 4/12/2007 | 4/20/2007 | N | 6.5 | 37 | D |
| SS052405 | 345 | 4/27/2006 | 4/27/2006 | C | 0 | 1 | T |
| HS060037 | 335 | 5/16/2006 | 5/16/2006 | D | 7 | 10 | F |
| SS060529 | 335 | 5/1/2006 | 5/4/2006 | D | 6.5 | 10 | F |
| HL070352 | 330 | 3/7/2007 | 3/7/2007 | T | 0 | 0 | X |
| SS070017 | 331 | 1/9/2007 | 1/9/2007 | D | 6.5 | 6.5 | J |
| SL060896 | 342 | 1/17/2007 | 1/17/2007 | A | 0 | 1 | X |
| SS060575 | 341 | 9/15/2006 | 9/15/2006 | A | 5.5 | 5.5 | T |
| HS060489 | 345 | 11/2/2006 | 11/6/2006 | D | 6 | 16 | D |
| HL060898 | 330 | 3/1/2007 | 3/1/2007 | T | 0 | 1 | X |
| SS051417 | 341 | 9/26/2006 | 9/26/2006 | X | 5.5 | 5.5 | X |

Figure 6-11. Example of Access Query for Category III

For each project cost category five spreadsheets for the Architect, Electrical, Mechanical, Structural and Fire, Life, and Safety reviewer was created, resulting in a total of twenty spreadsheets. Figure 6-12 shows a screenshot from the spreadsheet for construction projects greater than $1M and less than or equal to $10M. This particular spreadsheet of data is for the structural review. Highlighted is row 27, this information comes from the Access database except for column I (Days column) which shows the computed number of days between when the structural reviewer finished their project review. In this instance, the number of days is twenty.

The number of days is calculated for thirty data points for each of the disciplines and is the data set that is then used to run a resampling analysis to obtain the mean and standard deviation for each of the review times in each of the categories.



Microsoft Excel - Mean and SD Inputs.xls

File Edit View Insert Format Tools Data Window Help Adobe PDF

Arial

Reply with Changes... End Review...

L27

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ReviewID | ProjNum | ACT | STRUN | STRUI | STRUO | STRUDF | STRHRS | Days | |
| 26 | 218692 | HL060696 | 331 | GCC | 15-Nov-06 | 08-Dec-06 | D | 64 | 24 | |
| 27 | 216693 | SL050712 | 331 | MCL | 29-Sep-06 | 18-Oct-06 | D | 21 | 20 | |
| 28 | 224748 | SL062366 | 331 | RDK | 11-Jan-07 | 18-Jan-07 | D | 21 | 8 | |
| 29 | 233312 | SS070597 | 331 | TTK | 03-May-07 | 21-May-07 | N | 21 | 19 | |
| 30 | 222011 | SL060712 | 331 | ZGZ | 18-Jan-07 | 24-Jan-07 | N | 21 | 7 | |
| 31 | 237524 | SS071007 | 331 | IRK | | | T | 21 | | |
| 32 | 227812 | HL060898 | 331 | RDK | 10-Apr-07 | 25-Apr-07 | N | 21 | 16 | |
| 33 | 210743 | SL060784 | 331 | KSC | 27-Jun-06 | 06-Jul-06 | D | 21 | 10 | |
| 34 | 208022 | SS060251 | 331 | CXL | 05-May-06 | 09-May-06 | D | 21 | 5 | |
| 35 | 238137 | HS060883 | 331 | | | | T | 64 | | |
| 36 | 217126 | SS061777 | 331 | LCC | 24-Oct-06 | 25-Oct-06 | N | 21 | 2 | |
| 37 | 239236 | SL071452 | 331 | | | | T | 21 | | |
| 38 | 226503 | SL062372 | 331 | MYJ | 19-Mar-07 | 21-Mar-07 | D | 21 | 3 | |
| 39 | 211842 | SS052775 | 331 | CXL | 24-Jul-06 | 27-Jul-06 | D | 21 | 4 | |
| 40 | 237832 | HS071085 | 331 | HXB | 18-Jul-07 | 25-Jul-07 | D | 96 | 8 | |

StructMuSD (1M - 10M) / ArchMuSD (10M - 50M) / ElectMuSD (10M - 50M) / FLSMuSD (10M

Ready

Figure 6-12 Spreadsheet of Values

Tables 6-7 and 6-8 show the consolidated review times and standard deviations for the first review used in the discrete event simulation for alternative review.

| Category | ArchMu | ArchSD | ElectMu | ElectSD | FLSMu | FLSSD |
|---|---|---|---|---|---|---|
| I | 1.17 | 0.17 | 1.067 | 0.047 | 1.36 | 0.21 |
| II | 1.66 | 0.26 | 1.17 | 0.068 | 1.38 | 0.22 |
| III | 2.85 | 0.7 | 4.39 | 1.26 | 4.02 | 0.76 |
| IV | 8.38 | 1.82 | 8.26 | 1.89 | 18.2 | 3.43 |

Table 6-7 Consolidated First Review Mean and Standard Deviation

| Category | MechMu | MechSD | StructMu | StructSD |
|---|---|---|---|---|
| I | 1.07 | 0.046 | 1.85 | 0.4 |
| II | 3.79 | 1.97 | 2.59 | 0.4 |
| III | 4.37 | 0.78 | 8.32 | 1.11 |
| IV | 10.88 | 2.38 | 21.5 | 6.25 |

Table 6-8 Consolidated First Review Mean and Standard Deviation

The same process was used to calculate the rework review times. Figure 6-13 shows a spreadsheet similar to the one shown in figure 6-12 except that it has been sorted by 34* numbers which represent projects that are taken back in for review after the projects have been reworked by the design team. The highlighted row (no. 179) shows the project number, the activity code (341), the FLS reviewer and the date the project was taken in and then signed out (15 Nov 06 to 5 Dec 06) for a total of 22 days.

| | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|
| 1 | ProjNum | ACT | FLSON | FLSOI | FLSOO | FLSODF | FLSHRS | Days |
| 171 | SS051777 | 341 | WHC | 07-Feb-07 | 07-Feb-07 | C | 2 | 1 |
| 172 | ES051097 | 341 | X | | | | 0 | |
| 173 | HS022427 | 341 | CHM | 19-Apr-06 | 12-May-06 | X | 0 | |
| 174 | SL060046 | 341 | DGC | 13-Mar-07 | 19-Mar-07 | D | 2 | 7 |
| 175 | SS051015 | 341 | X | | | X | 0 | |
| 176 | HS062067 | 341 | X | | | X | 0 | |
| 177 | SS050767 | 341 | X | | | | 0 | |
| 178 | HS062067 | 341 | X | | | X | 0 | |
| 179 | SL060896 | 341 | JPH | 15-Nov-06 | 05-Dec-06 | D | 2 | 22 |
| 180 | SS060917 | 341 | SSW | 04-Apr-07 | 06-Apr-07 | D | 2 | 3 |
| 181 | ES052229 | 341 | X | | | | 0 | |
| 182 | SL050208 | 341 | SDF | 23-Feb-06 | 24-Feb-06 | D | 2 | 2 |
| 183 | SS041089 | 341 | JCM | 04-Apr-06 | 04-Apr-06 | A | 2 | 1 |
| 184 | HL060696 | 341 | X | | | X | 0 | |
| 185 | SS060575 | 341 | JCM | 14-Sep-06 | 14-Sep-06 | A | 2 | 1 |
| 186 | SS050743 | 341 | JCM | 10-Oct-06 | 11-Oct-06 | A | 2 | 1 |
| 187 | SS052745 | 341 | JSD | 12-Apr-06 | 13-Apr-06 | A | 2 | 2 |
| 188 | HS050255 | 341 | SSW | 27-Feb-06 | 03-Mar-06 | D | 3 | 5 |
| 189 | HS041907 | 341 | X | | | | 0 | |
| 190 | ES051097 | 341 | X | | | | 0 | |
| 191 | HS022427 | 341 | RAD | 16-Oct-06 | 20-Oct-06 | D | 3 | 5 |
| 192 | HS052393 | 341 | X | | | X | 0 | |
| 193 | SS060631 | 341 | JCM | 11-Oct-06 | 12-Oct-06 | C | 2 | 2 |
| 194 | HS070423 | 341 | HDH | 22-Jun-07 | 22-Jun-07 | C | 3 | 1 |
| 195 | SL060266 | 341 | DTM | 02-Aug-06 | 02-Aug-06 | D | 2 | 1 |
| 196 | SS060917 | 341 | CHM | 01-May-07 | 01-May-07 | A | 2 | 1 |
| 197 | SS051015 | 341 | RAD | 02-Aug-06 | 02-Aug-06 | A | 2 | 1 |
| 198 | SL062302 | 341 | JAC | 24-Apr-07 | 26-Apr-07 | N | 0 | 3 |
| 199 | SS061429 | 341 | WHC | 05-Feb-07 | 06-Feb-07 | D | 2 | 2 |
| 200 | SS052247 | 341 | CHL | 10-Apr-06 | 10-Apr-06 | D | 2 | 1 |
| 201 | SS052165 | 341 | JCM | 05-Jul-06 | 06-Jul-06 | D | 1.5 | 2 |
| 202 | SL061082 | 341 | DTM | 15-Dec-06 | 15-Dec-06 | D | 2 | 1 |

Figure 6-13 Spreadsheet of FLSMuSD Category III (1M - 10M)

A similar resampling technique was used to get the mean and standard deviations for the time to re-review projects that had to be reworked. A summary of those values is listed in Table 6-9 and 6-10.

| Category | ArchMu | ArchSD | ElectMu | ElectSD | FLSMu | FLSSD |
|---|---|---|---|---|---|---|
| I | 1.44 | 0.42 | 1.03 | 0.03 | 1.34 | 0.19 |
| II | 1.68 | 0.26 | 1.07 | 0.04 | 1.96 | 0.32 |
| III | 1.6 | 0.29 | 1.44 | 0.2 | 4.19 | 1.17 |
| IV | 4.05 | 1.53 | 2.7 | 0.72 | 7.57 | 1.8 |

Table 6-9 Consolidated Mean and Standard Deviation Re-Review

| Category | MechMu | MechSD | StructMu | StructSD |
|---|---|---|---|---|
| I | 1.39 | 0.25 | 1.17 | 0.09 |
| II | 1.17 | 0.2 | 2.3 | 0.49 |
| III | 1.82 | 0.45 | 6.04 | 0.92 |
| IV | 4.8 | 1.51 | 10.8 | 2.9 |

Table 6-10 Consolidated Mean and Standard Deviation Re-Review

Figure 6-14 compares the first review times with the re-review times. For categories I and II the first and re-review times are relatively unchanged. This makes sense because the drawings are not as complex as the higher category projects and since the data in the logbook is kept by days a project is very likely to take around a day to a day-and-half to review. However, category IV projects the mean time for re-review are dramatically smaller than the mean time for the first review. This is consistent with the organization since the re-review is conducted by the same reviewer so he/she already has a sense of the design drawings the re-review times are expected to be less.

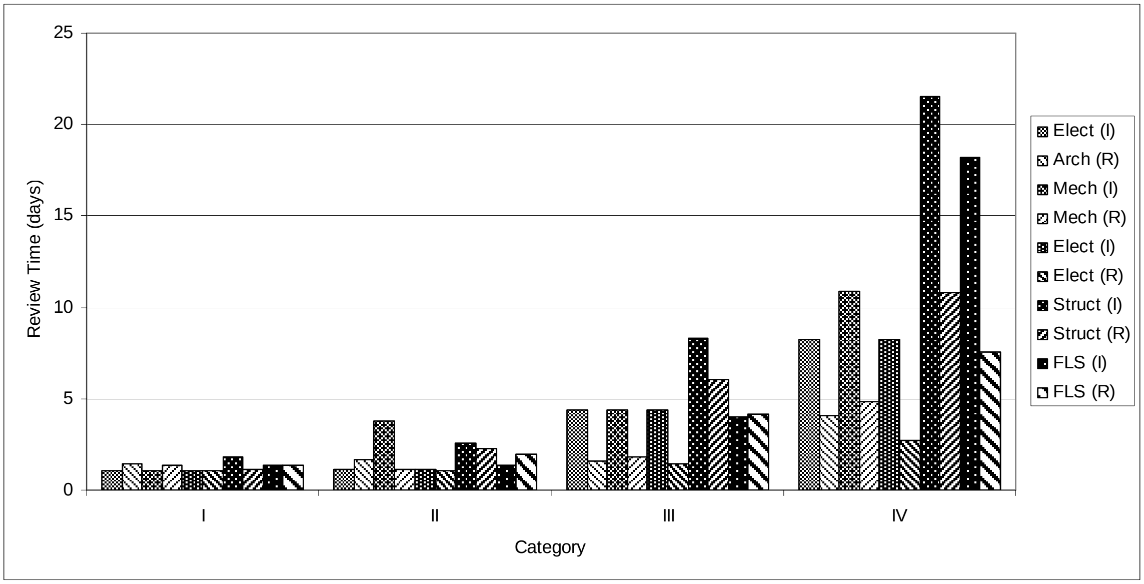
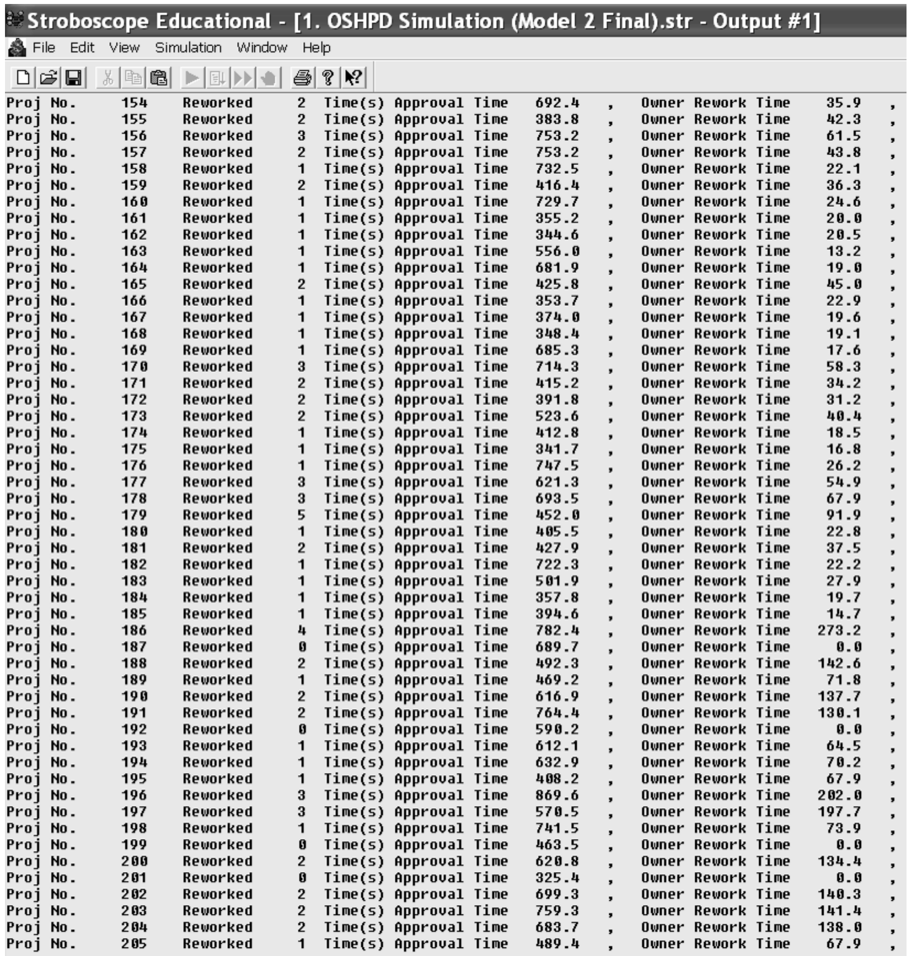



Figure 6-14 Mean Times for Initial Review and Re-Review by Discipline

### 6.9.7 Determining Time to Permit

Ultimately, the goal of the simulation models is to determine the time to permit a drawing set and determine the impact of process changes through multiple iterations. Figure 6-15 shows example model output where the model is loaded with 205 projects. Category I has 50 projects, category II has 100 projects, category III has 35 projects and category IV has 20 projects. Figure 6-15 shows the projects sorted by project number. The completion time is calculated by subtracting the complete time from the first time that the project was reviewed. For example project number 205 is completed in 489.4 or 490 days. In addition, the number of times a project is reworked versus its overall time to permit is also evaluated.




```
Proj No.   154   Reworked   2  Time(s) Approval Time   692.4  ,  Owner Rework Time    35.9  ,
Proj No.   155   Reworked   2  Time(s) Approval Time   383.8  ,  Owner Rework Time    42.3  ,
Proj No.   156   Reworked   3  Time(s) Approval Time   753.2  ,  Owner Rework Time    61.5  ,
Proj No.   157   Reworked   2  Time(s) Approval Time   753.2  ,  Owner Rework Time    43.8  ,
Proj No.   158   Reworked   1  Time(s) Approval Time   732.5  ,  Owner Rework Time    22.1  ,
Proj No.   159   Reworked   2  Time(s) Approval Time   416.4  ,  Owner Rework Time    36.3  ,
Proj No.   160   Reworked   1  Time(s) Approval Time   729.7  ,  Owner Rework Time    24.6  ,
Proj No.   161   Reworked   1  Time(s) Approval Time   355.2  ,  Owner Rework Time    20.0  ,
Proj No.   162   Reworked   1  Time(s) Approval Time   344.6  ,  Owner Rework Time    20.5  ,
Proj No.   163   Reworked   1  Time(s) Approval Time   556.0  ,  Owner Rework Time    13.2  ,
Proj No.   164   Reworked   1  Time(s) Approval Time   681.9  ,  Owner Rework Time    19.0  ,
Proj No.   165   Reworked   2  Time(s) Approval Time   425.8  ,  Owner Rework Time    45.0  ,
Proj No.   166   Reworked   1  Time(s) Approval Time   353.7  ,  Owner Rework Time    22.9  ,
Proj No.   167   Reworked   1  Time(s) Approval Time   374.0  ,  Owner Rework Time    19.6  ,
Proj No.   168   Reworked   1  Time(s) Approval Time   348.4  ,  Owner Rework Time    19.1  ,
Proj No.   169   Reworked   1  Time(s) Approval Time   685.3  ,  Owner Rework Time    17.6  ,
Proj No.   170   Reworked   3  Time(s) Approval Time   714.3  ,  Owner Rework Time    58.3  ,
Proj No.   171   Reworked   2  Time(s) Approval Time   415.2  ,  Owner Rework Time    34.2  ,
Proj No.   172   Reworked   2  Time(s) Approval Time   391.8  ,  Owner Rework Time    31.2  ,
Proj No.   173   Reworked   2  Time(s) Approval Time   523.6  ,  Owner Rework Time    40.4  ,
Proj No.   174   Reworked   1  Time(s) Approval Time   412.8  ,  Owner Rework Time    18.5  ,
Proj No.   175   Reworked   1  Time(s) Approval Time   341.7  ,  Owner Rework Time    16.8  ,
Proj No.   176   Reworked   1  Time(s) Approval Time   747.5  ,  Owner Rework Time    26.2  ,
Proj No.   177   Reworked   3  Time(s) Approval Time   621.3  ,  Owner Rework Time    54.9  ,
Proj No.   178   Reworked   3  Time(s) Approval Time   693.5  ,  Owner Rework Time    67.9  ,
Proj No.   179   Reworked   5  Time(s) Approval Time   452.0  ,  Owner Rework Time    91.9  ,
Proj No.   180   Reworked   1  Time(s) Approval Time   405.5  ,  Owner Rework Time    22.8  ,
Proj No.   181   Reworked   2  Time(s) Approval Time   427.9  ,  Owner Rework Time    37.5  ,
Proj No.   182   Reworked   1  Time(s) Approval Time   722.3  ,  Owner Rework Time    22.2  ,
Proj No.   183   Reworked   1  Time(s) Approval Time   501.9  ,  Owner Rework Time    27.9  ,
Proj No.   184   Reworked   1  Time(s) Approval Time   357.8  ,  Owner Rework Time    19.7  ,
Proj No.   185   Reworked   1  Time(s) Approval Time   394.6  ,  Owner Rework Time    14.7  ,
Proj No.   186   Reworked   4  Time(s) Approval Time   782.4  ,  Owner Rework Time   273.2  ,
Proj No.   187   Reworked   0  Time(s) Approval Time   689.7  ,  Owner Rework Time     0.0  ,
Proj No.   188   Reworked   2  Time(s) Approval Time   492.3  ,  Owner Rework Time   142.6  ,
Proj No.   189   Reworked   1  Time(s) Approval Time   469.2  ,  Owner Rework Time    71.8  ,
Proj No.   190   Reworked   2  Time(s) Approval Time   616.9  ,  Owner Rework Time   137.7  ,
Proj No.   191   Reworked   2  Time(s) Approval Time   764.4  ,  Owner Rework Time   130.1  ,
Proj No.   192   Reworked   0  Time(s) Approval Time   590.2  ,  Owner Rework Time     0.0  ,
Proj No.   193   Reworked   1  Time(s) Approval Time   612.1  ,  Owner Rework Time    64.5  ,
Proj No.   194   Reworked   1  Time(s) Approval Time   632.9  ,  Owner Rework Time    70.2  ,
Proj No.   195   Reworked   1  Time(s) Approval Time   408.2  ,  Owner Rework Time    67.9  ,
Proj No.   196   Reworked   3  Time(s) Approval Time   869.6  ,  Owner Rework Time   202.0  ,
Proj No.   197   Reworked   3  Time(s) Approval Time   570.5  ,  Owner Rework Time   197.7  ,
Proj No.   198   Reworked   1  Time(s) Approval Time   741.5  ,  Owner Rework Time    73.9  ,
Proj No.   199   Reworked   0  Time(s) Approval Time   463.5  ,  Owner Rework Time     0.0  ,
Proj No.   200   Reworked   2  Time(s) Approval Time   620.8  ,  Owner Rework Time   134.4  ,
Proj No.   201   Reworked   0  Time(s) Approval Time   325.4  ,  Owner Rework Time     0.0  ,
Proj No.   202   Reworked   2  Time(s) Approval Time   699.3  ,  Owner Rework Time   140.3  ,
Proj No.   203   Reworked   2  Time(s) Approval Time   759.3  ,  Owner Rework Time   141.4  ,
Proj No.   204   Reworked   2  Time(s) Approval Time   683.7  ,  Owner Rework Time   138.0  ,
Proj No.   205   Reworked   1  Time(s) Approval Time   489.4  ,  Owner Rework Time    67.9  ,
```

Figure 6-15 Simulation Output Showing Project Numbers, Number of Rework Cycles, Approval Time and Owner Rework Time in Days

Table 6-11 is a compilation of mean time to permit for three situations. The first column represents the four categories of projects. The second column represents data taken from the FDD on the mean time to permit for 2007. The third and fourth columns show the mean time to permit and the standard deviation of model 1. Model 1 represents one plan review region with constrained personnel resources. The fifth and sixth columns show the mean time to permit and the standard deviations of model 2. Model 2 represents one plan review region but has double the review personnel. These additional review personnel are dedicated to reviewing projects requiring rework.

| Category | Mean (FDD) | Mean (Model 1) | SD | Mean (Model 2) | SD |
|---|---|---|---|---|---|
| I | 36 | 36 | 14.4 | 32 | 12.4 |
| II | 180 | 188 | 80.9 | 160 | 70.2 |
| III | 480 | 572 | 151.0 | 449 | 104.6 |
| IV | 660 | 636 | 181.0 | 508 | 110.5 |

Table 6-11 Mean Time to Permit

Figure 6-16 graphically represents the data shown in table 6-11. Along the x-axis are the four categories of projects. The y-axis represents the mean time to permit expressed in days. The first column of each category represents the 2007 data obtained from the FDD. The second column represents the mean time to permit for model 1. The third column represents the same for model 2. Included are the standard deviations for each of the categories.

Figure 6-16 shows that model 1 matches the FDD data relatively well. Indeed it was the intent to calibrate model 1 with real data. Model 2 shows mean times to permit lower than model 1. This result is expected because model 2 has more personnel resources available, and this personally reduces the time to permit. Figure 6-16 provides confidence the two models realistically simulate system behavior of the FDD.

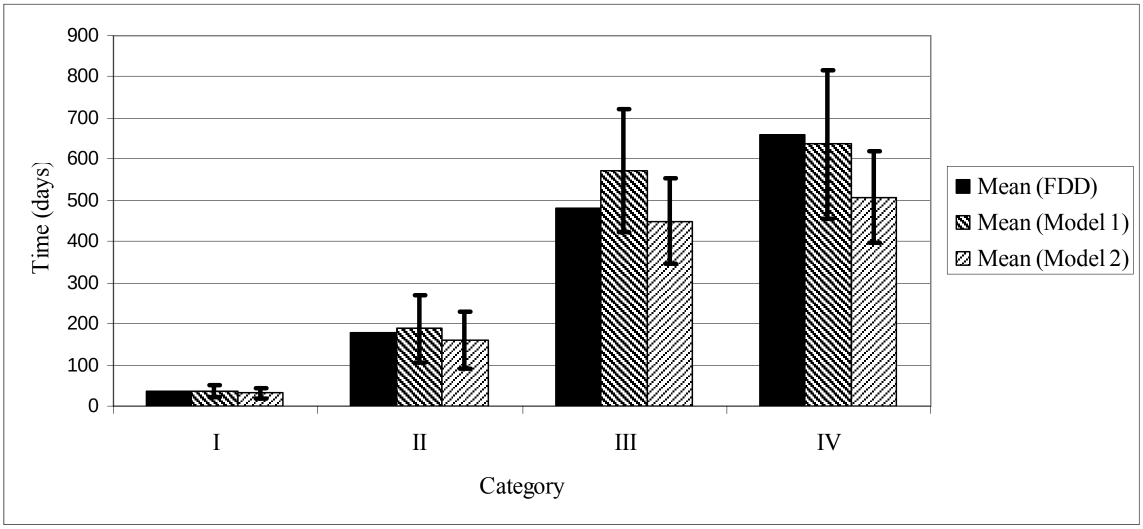



Figure 6-16 Mean Time to Permit Analysis Comparing FDD Data to Simulation Model Output

Figure 6-17 shows projects in category II, costing between \$50K and \$1M. The graph shows the average time to permit is 180 days but it also shows gaps at times when no project permits are issued (e.g., during the New Year and the Fourth of July). The vertical lines on figure 6-17 show the overall time to permit for a project and when the project was approved.

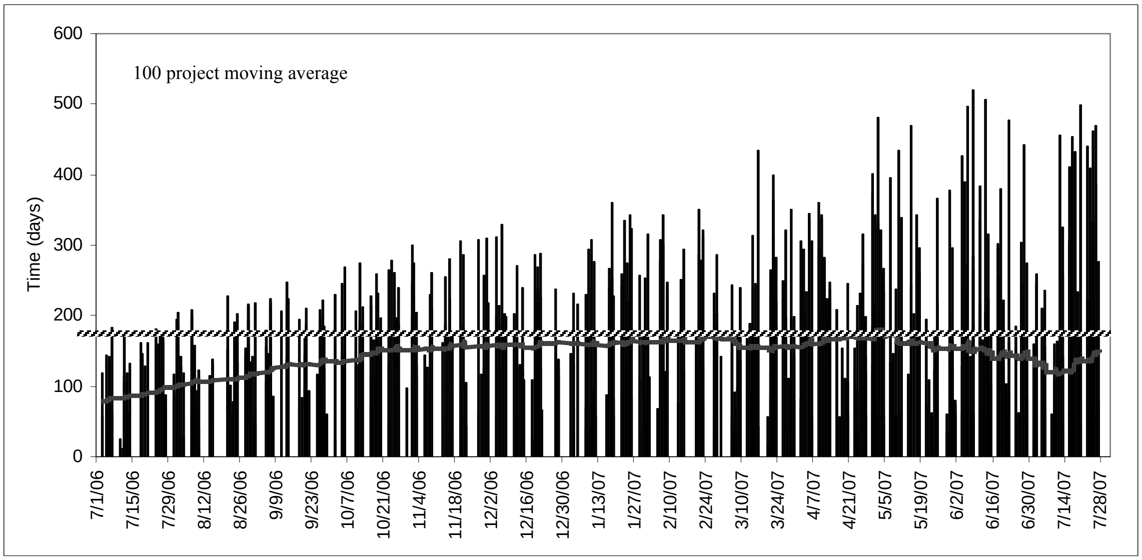



Figure 6-17 Real Time Category II

Figure 6-18 shows a sliding four week scale of the time to permit a healthcare facility. The two light grey lines above and below the black line, represent one standard deviation from the mean time to permit for category II. The time to permit hovers around 180 days and the graph shows no significant seasonal effects.

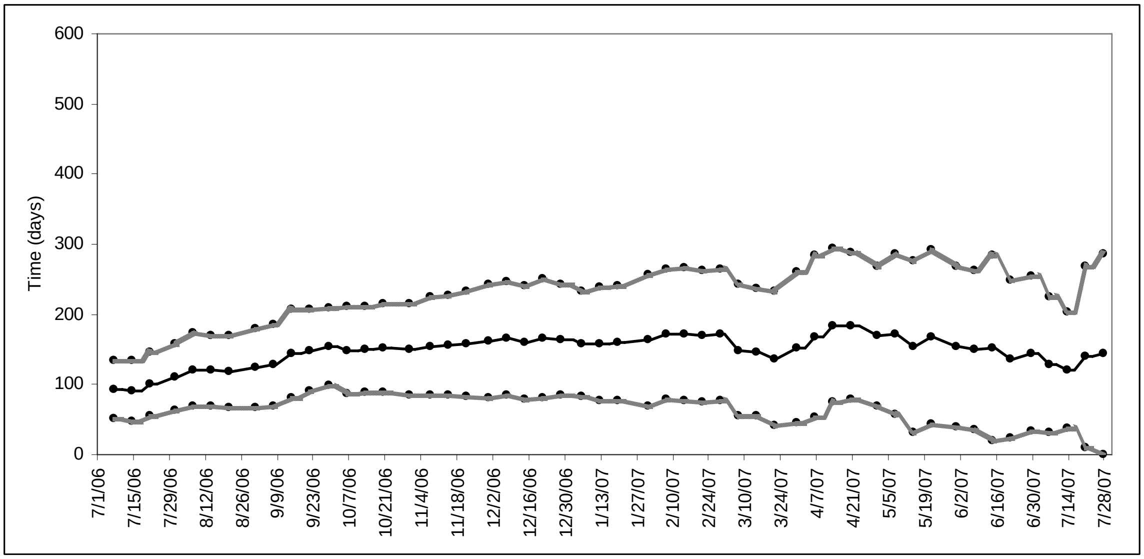



Figure 6-18 Real Time Category II (4 Week Moving Average)

Figure 6-19 shows when individual category III projects were permitted and how much time the review required. This category represents larger projects over a two year time frame. The average time to permit is approximately 200 days. No seasonal effects appear to affect the time to permit.

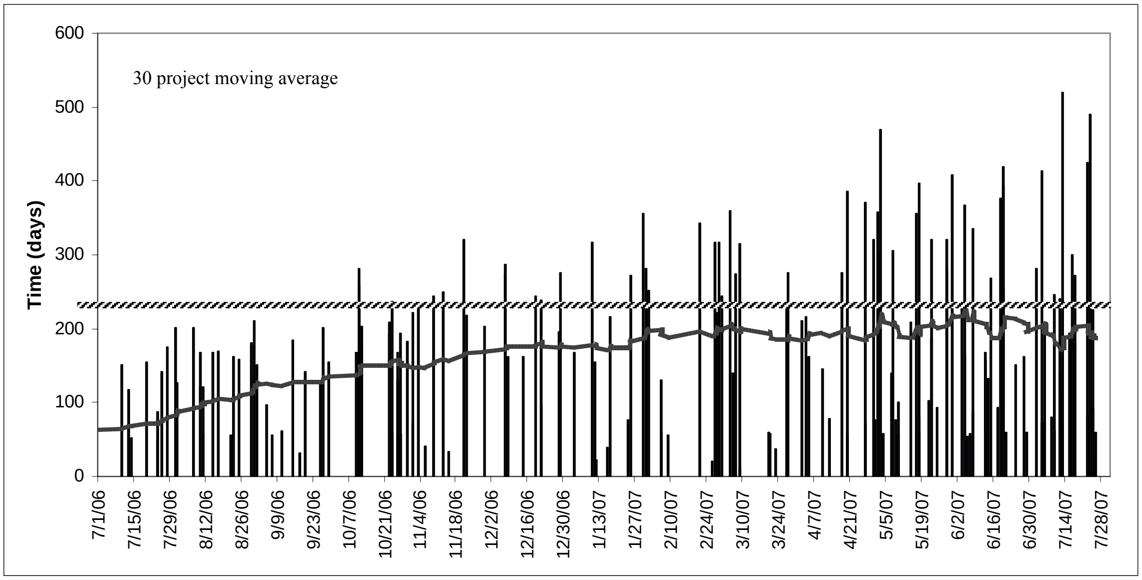



Figure 6-19 Real Time Category III

Figure 6-20 shows a four-week moving scale of the time to permit healthcare facility drawings for category III projects. Again the data does not provide any insight into seasonal effects to the time to permit a healthcare facility. The light grey lines represent plus and minus one standard deviation of the sample data.

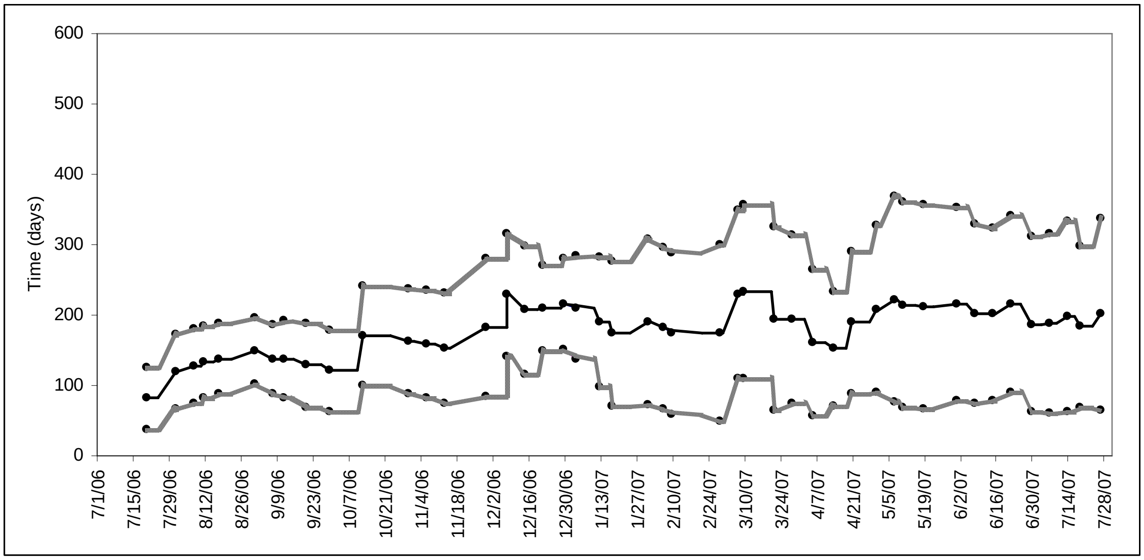



Figure 6-20 Real Time Category III (4-Week Moving Average)

Figure 6-21 shows a ten project moving average for category IV projects. A larger time between projects is the result of fewer projects within the category versus the other three categories requiring approval. This data presents the time to permit reaching 400 days. The increase in the time to permit may be attributed to the increase in the number of category IV projects being submitted, thereby requiring more staff time for their review. As the workload increases, the time to permit increases as well all other things being equal.

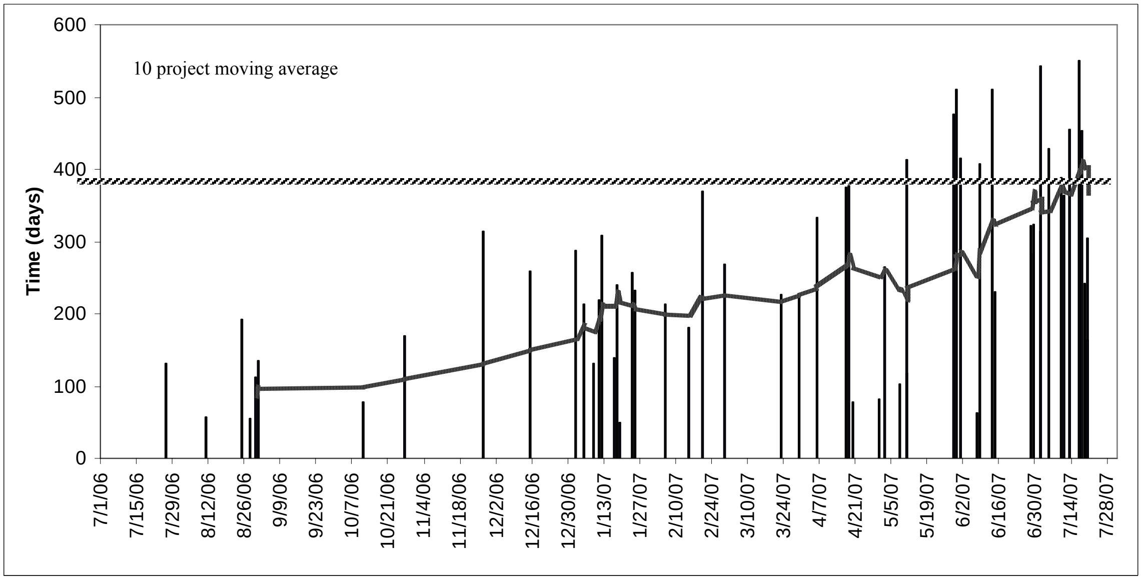



Figure 6-21 Real Time Category IV

Figure 6-22 shows a real time moving average for category IV projects. The data is not smooth due to the limited number of projects that fall into this category. However, the average time to permit is similar to figure 6-21.

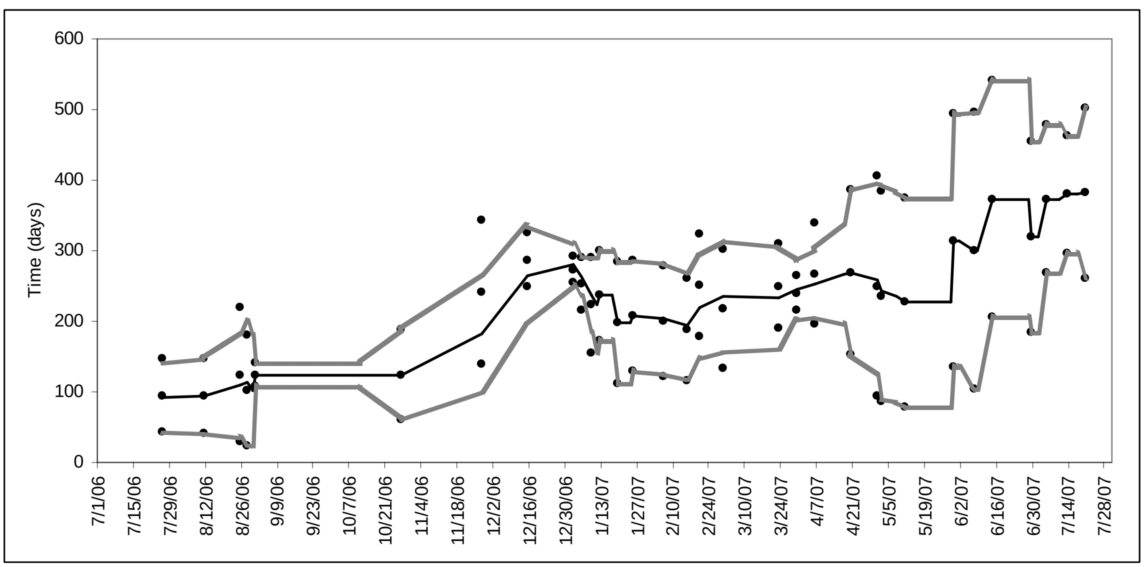



Figure 6-22 Real Time Category IV (4-Week Moving Average)

Tables 6-12 to 6-15 show the mean time to permit and the corresponding owner rework time for each of the four categories. The tables break down the approval times by number of rework instances. For example I (1R) stands for category I with one instance of rework. The tables show the mean time to permit and owner rework time increases with the number of rework cycles. This is an expected result.

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Category | Approval | SD | Owner | SD | Approval | SD | Owner | SD |
| I (All) | 36 | 14.4 | 6 | 5.0 | 32 | 12.4 | 8 | 4.8 |
| I (0R) | 30 | 13.7 | N/A | N/A | 8 | 9.1 | N/A | N/A |
| I (1R) | 34 | 13.1 | 5 | 1.0 | 29 | 10.4 | 5 | 1.0 |
| I (2R) | 42 | 13.0 | 10 | 1.3 | 37 | 11.0 | 10 | 1.4 |
| I (3+R) | 46 | 15.7 | 16 | 3.5 | 46 | 11.5 | 16 | 1.9 |

Table 6-12 Category I: Approval and Owner Rework Time (days), Models 1 and 2

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Category | Approval | SD | Owner | SD | Approval | SD | Owner | SD |
| II (All) | 188 | 80.9 | 17 | 11.3 | 160 | 70.2 | 16 | 9.7 |
| II (0R) | 147 | 73.9 | N/A | N/A | 134 | 63.2 | N/A | N/A |
| II (1R) | 172 | 75.8 | 10 | 2.0 | 151 | 67.2 | 10 | 2.0 |
| II (2R) | 196 | 78.8 | 20 | 2.8 | 164 | 69.5 | 20 | 2.6 |
| II (3+R) | 222 | 81.5 | 34 | 7.7 | 186 | 75.3 | 33 | 6.6 |

Table 6-13 Category II: Approval and Owner Rework Time (days), Models 1 and 2

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Category | Approval | SD | Owner | SD | Approval | SD | Owner | SD |
| III (All) | 572 | 151.0 | 40 | 25.6 | 449 | 104.6 | 33 | 17.4 |
| III (0R) | 314 | 9.1 | N/A | N/A | 465 | 50.8 | N/A | N/A |
| III (1R) | 534 | 148.9 | 20 | 2.9 | 440 | 102.0 | 20 | 2.8 |
| III (2R) | 585 | 128.5 | 40 | 4.2 | 440 | 108.4 | 40 | 4.1 |
| III (3+R) | 633 | 149.4 | 75 | 21.7 | 488 | 102.8 | 63 | 7.5 |

Table 6-14 Category III: Approval and Owner Rework Time (days), Models 1 and 2

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Category | Approval | SD | Owner | SD | Approval | SD | Owner | SD |
| IV (All) | 636 | 181.1 | 115 | 80.4 | 508 | 110.5 | 94 | 63.8 |
| IV (0R) | 466 | 168.9 | N/A | N/A | 458 | 100.6 | N/A | N/A |
| IV (1R) | 584 | 157.2 | 70 | 4.4 | 484 | 102.5 | 70 | 4.5 |
| IV (2R) | 696 | 149.7 | 142 | 6.4 | 534 | 100.0 | 139 | 7.0 |
| IV (3+R) | 786 | 172.3 | 260 | 59.8 | 621 | 110.1 | 224 | 30.5 |

Table 6-15 Category IV: Approval and Owner Rework Time (days), Models 1 and 2

## 6.10 Sensitivity Analysis

I conducted five sensitivity analyses to determine the effect of an alternative review process on the time to permit. The first sensitivity analyses utilized a one to one relationship. Realizing that to shift the design curve to the left requires more work upfront, I wanted to determine what would happen if the first review times were increased with a corresponding one to one (1:1) relationship in the decrease in rework percentage and re-review times. Therefore a 10% increase in the first review would result in a 10% reduction in the chance for rework to occur and 10% reduction in the subsequent re-review time. The sensitivity analysis will only occur with category IV. This occurs because currently the alternative review process through OSHPD is limited to large projects. Therefore category IV review times and rework will be used for category five and then varied between 10% and 50%.

| **Variable** | **Initial** | **10%** | **20%** | **30%** | **40%** | **50%** | **60%** | **70%** | **80%** | **90%** | **99%** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ArchMu | 8.38 | 9.22 | 10.06 | 10.89 | 11.73 | 12.57 | 13.41 | 14.25 | 15.08 | 15.92 | 16.68 |
| ArchSD | 1.82 | 1.64 | 1.46 | 1.27 | 1.09 | 0.91 | 0.73 | 0.55 | 0.36 | 0.18 | 0.02 |
| StructMu | 21.50 | 23.65 | 25.80 | 27.95 | 30.10 | 32.25 | 34.40 | 36.55 | 38.70 | 40.85 | 42.79 |
| StructSD | 6.25 | 5.63 | 5.00 | 4.38 | 3.75 | 3.13 | 2.50 | 1.88 | 1.25 | 0.63 | 0.06 |
| MechMu | 10.90 | 11.99 | 13.08 | 14.17 | 15.26 | 16.35 | 17.44 | 18.53 | 19.62 | 20.71 | 21.69 |
| MechSD | 2.38 | 2.14 | 1.90 | 1.67 | 1.43 | 1.19 | 0.95 | 0.71 | 0.48 | 0.24 | 0.02 |
| ElectMu | 8.27 | 9.10 | 9.92 | 10.75 | 11.58 | 12.41 | 13.23 | 14.06 | 14.89 | 15.71 | 16.46 |
| ElectSD | 1.94 | 1.75 | 1.55 | 1.36 | 1.16 | 0.97 | 0.78 | 0.58 | 0.39 | 0.19 | 0.02 |
| FLSMu | 18.20 | 20.02 | 21.84 | 23.66 | 25.48 | 27.30 | 29.12 | 30.94 | 32.76 | 34.58 | 36.22 |
| FLSSD | 3.43 | 3.09 | 2.74 | 2.40 | 2.06 | 1.72 | 1.37 | 1.03 | 0.69 | 0.34 | 0.03 |

Table 6-16 (1:1) Sensitivity Analysis Ratios for First Review

Table 6-16 shows the first review variables. The second column shows the initial times used for category IV characteristics. The additional columns represent the numbers used for the sensitivity analysis. Table 6-17 shows the re-review variables.

| **Variable** | **Initial** | **-10%** | **-20%** | **-30%** | **-40%** | **-50%** | **-60%** | **-70%** | **-80%** | **-90%** | **-99%** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| r | 88 | 79.2 | 70.4 | 61.6 | 52.8 | 44 | 35.2 | 26.4 | 17.6 | 8.8 | 0.88 |
| ORewMu | 70 | 63 | 56 | 49 | 42 | 35 | 28 | 21 | 14 | 7 | 0.7 |
| RRevAMu | 4.05 | 3.65 | 3.24 | 2.84 | 2.43 | 2.03 | 1.62 | 1.22 | 0.81 | 0.41 | 0.04 |
| RRevASD | 1.53 | 1.38 | 1.22 | 1.07 | 0.92 | 0.77 | 0.61 | 0.46 | 0.31 | 0.15 | 0.02 |
| RRevSMu | 10.80 | 9.72 | 8.64 | 7.56 | 6.48 | 5.40 | 4.32 | 3.24 | 2.16 | 1.08 | 0.11 |
| RRevSSD | 2.90 | 2.61 | 2.32 | 2.03 | 1.74 | 1.45 | 1.16 | 0.87 | 0.58 | 0.29 | 0.03 |
| RRevMMu | 4.80 | 4.32 | 3.84 | 3.36 | 2.88 | 2.40 | 1.92 | 1.44 | 0.96 | 0.48 | 0.05 |
| RRevMSD | 1.51 | 1.36 | 1.21 | 1.06 | 0.91 | 0.76 | 0.60 | 0.45 | 0.30 | 0.15 | 0.02 |
| RRevEMu | 2.70 | 2.43 | 2.16 | 1.89 | 1.62 | 1.35 | 1.08 | 0.81 | 0.54 | 0.27 | 0.03 |
| RRevESD | 0.72 | 0.65 | 0.58 | 0.50 | 0.43 | 0.36 | 0.29 | 0.22 | 0.14 | 0.07 | 0.01 |
| RRevFMu | 7.60 | 6.84 | 6.08 | 5.32 | 4.56 | 3.80 | 3.04 | 2.28 | 1.52 | 0.76 | 0.08 |
| RRevFSD | 1.80 | 1.62 | 1.44 | 1.26 | 1.08 | 0.90 | 0.72 | 0.54 | 0.36 | 0.18 | 0.02 |

Table 6-17 (1:1) Sensitivity Analysis Ratios for Re-Review

To test the effect of rework and alternative on review on the system a sensitivity analysis was conducted to determine the impact of variables on the system. The following table shows the variable of concern and the range of which the analysis was conducted. To summarize, the first review times were considered to vary from 10 - 50%. The re-review times were also set to vary from 10 - 50%. The owner rework time was also varied from 10 - 50% and the rework factor was also changed to conduct the sensitivity analysis.

Recognizing the fact that alternative review takes up more time initially constitutes the reason why the first review times are increased from 10 - 50%. Conversely, with alternative review, the time to conduct a rework cycle and for re-review to occur will be less. In this sensitivity analysis the factors were used in a linear fashion. For example, with an increase of 10% in first review results in a 10% decrease in the time for owner rework, re-review, and a rework factor.

The second sensitivity analysis utilized a one to two (1:2) ratio. Whereby a 10% increase in first review results in a 20% reduction in the chance of rework and 20% reduction in the re-review time. Located in tables 6-18 and 6-19 are the category IV inputs.

| Variable | Initial | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ArchMu | 8.38 | 8.80 | 9.22 | 9.64 | 10.06 | 10.48 | 10.89 | 11.31 | 11.73 | 12.15 | 12.57 |
| ArchSD | 1.82 | 1.73 | 1.64 | 1.55 | 1.46 | 1.37 | 1.27 | 1.18 | 1.09 | 1.00 | 0.91 |
| StructMu | 21.50 | 22.58 | 23.65 | 24.73 | 25.80 | 26.88 | 27.95 | 29.03 | 30.10 | 31.18 | 32.25 |
| StructSD | 6.25 | 5.94 | 5.63 | 5.31 | 5.00 | 4.69 | 4.38 | 4.06 | 3.75 | 3.44 | 3.13 |
| MechMu | 10.90 | 11.45 | 11.99 | 12.54 | 13.08 | 13.63 | 14.17 | 14.72 | 15.26 | 15.81 | 16.35 |
| MechSD | 2.38 | 2.26 | 2.14 | 2.02 | 1.90 | 1.79 | 1.67 | 1.55 | 1.43 | 1.31 | 1.19 |
| ElectMu | 8.27 | 8.68 | 9.10 | 9.51 | 9.92 | 10.34 | 10.75 | 11.16 | 11.58 | 11.99 | 12.41 |
| ElectSD | 1.94 | 1.84 | 1.75 | 1.65 | 1.55 | 1.46 | 1.36 | 1.26 | 1.16 | 1.07 | 0.97 |
| FLSMu | 18.20 | 19.11 | 20.02 | 20.93 | 21.84 | 22.75 | 23.66 | 24.57 | 25.48 | 26.39 | 27.30 |
| FLSSD | 3.43 | 3.26 | 3.09 | 2.92 | 2.74 | 2.57 | 2.40 | 2.23 | 2.06 | 1.89 | 1.72 |

Table 6-18 (1:2) Sensitivity Analysis Ratios for First Review

| Variable | Initial | -10% | -20% | -30% | -40% | -50% | -60% | -70% | -80% | -90% | -99% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| r | 88 | 79.2 | 70.4 | 61.6 | 52.8 | 44 | 35.2 | 26.4 | 17.6 | 8.8 | 0.88 |
| ORewMu | 70 | 63 | 56 | 49 | 42 | 35 | 28 | 21 | 14 | 7 | 0.7 |
| RRevAMu | 4.05 | 3.65 | 3.24 | 2.84 | 2.43 | 2.03 | 1.62 | 1.22 | 0.81 | 0.41 | 0.04 |
| RRevASD | 1.53 | 1.38 | 1.22 | 1.07 | 0.92 | 0.77 | 0.61 | 0.46 | 0.31 | 0.15 | 0.02 |
| RRevSMu | 10.80 | 9.72 | 8.64 | 7.56 | 6.48 | 5.40 | 4.32 | 3.24 | 2.16 | 1.08 | 0.03 |
| RRevSSD | 2.90 | 2.61 | 2.32 | 2.03 | 1.74 | 1.45 | 1.16 | 0.87 | 0.58 | 0.29 | 0.11 |
| RRevMMu | 4.80 | 4.32 | 3.84 | 3.36 | 2.88 | 2.40 | 1.92 | 1.44 | 0.96 | 0.48 | 0.05 |
| RRevMSD | 1.51 | 1.36 | 1.21 | 1.06 | 0.91 | 0.76 | 0.60 | 0.45 | 0.30 | 0.15 | 0.02 |
| RRevEMu | 2.70 | 2.43 | 2.16 | 1.89 | 1.62 | 1.35 | 1.08 | 0.81 | 0.54 | 0.27 | 0.01 |
| RRevESD | 0.72 | 0.65 | 0.58 | 0.50 | 0.43 | 0.36 | 0.29 | 0.22 | 0.14 | 0.07 | 0.03 |
| RRevFMu | 7.60 | 6.84 | 6.08 | 5.32 | 4.56 | 3.80 | 3.04 | 2.28 | 1.52 | 0.76 | 0.08 |
| RRevFSD | 1.8 | 1.62 | 1.44 | 1.26 | 1.08 | 0.90 | 0.72 | 0.54 | 0.36 | 0.18 | 0.02 |

Table 6-19 (1:2) Sensitivity Analysis Ratios for Re-Review

The third sensitivity analysis utilized a one to four (1:4) ratio. Whereby a 10% increase in first review results in a 40% reduction in the chance of rework and a 40% reduction in the re-review time. Located in tables 6-20 and 6-21 are the category IV inputs.

| Variable | Initial | 5% | 10% | 15% | 20% | 25% |
|---|---|---|---|---|---|---|
| ArchMu | 8.38 | 8.80 | 9.22 | 9.64 | 10.06 | 10.48 |
| ArchSD | 1.82 | 1.91 | 2.00 | 2.09 | 2.18 | 2.28 |
| StructMu | 21.50 | 22.58 | 23.65 | 24.73 | 25.80 | 26.88 |
| StructSD | 6.25 | 6.56 | 6.88 | 7.19 | 7.50 | 7.81 |
| MechMu | 10.90 | 11.45 | 11.99 | 12.54 | 13.08 | 13.63 |
| MechSD | 2.38 | 2.50 | 2.62 | 2.74 | 2.86 | 2.98 |
| ElectMu | 8.27 | 8.68 | 9.10 | 9.51 | 9.92 | 10.34 |
| ElectSD | 1.94 | 2.04 | 2.13 | 2.23 | 2.33 | 2.43 |
| FLSMu | 18.20 | 19.11 | 20.02 | 20.93 | 21.84 | 22.75 |
| FLSSD | 3.43 | 3.60 | 3.77 | 3.94 | 4.12 | 4.29 |

Table 6-20 (1:4) Sensitivity Analysis Ratios for First Review

| Variable | Initial | -20% | -40% | -60% | -80% | -99% |
|---|---|---|---|---|---|---|
| r | 88 | 70.4 | 52.8 | 35.2 | 17.6 | 0.88 |
| ORewMu | 70 | 56 | 42 | 28 | 14 | 0.7 |
| RRevAMu | 4.05 | 3.24 | 2.43 | 1.62 | 0.81 | 0.04 |
| RRevASD | 1.53 | 1.22 | 0.92 | 0.61 | 0.31 | 0.02 |
| RRevSMu | 10.80 | 8.64 | 6.48 | 4.32 | 2.16 | 0.11 |
| RRevSSD | 2.90 | 2.32 | 1.74 | 1.16 | 0.58 | 0.03 |
| RRevMMu | 4.80 | 3.84 | 2.88 | 1.92 | 0.96 | 0.05 |
| RRevMSD | 1.51 | 1.21 | 0.91 | 0.60 | 0.30 | 0.02 |
| RRevEMu | 2.70 | 2.16 | 1.62 | 1.08 | 0.54 | 0.03 |
| RRevESD | 0.72 | 0.58 | 0.43 | 0.29 | 0.14 | 0.01 |
| RRevFMu | 7.60 | 6.08 | 4.56 | 3.04 | 1.52 | 0.08 |
| RRevFSD | 1.8 | 1.44 | 1.08 | 0.72 | 0.36 | 0.018 |

Table 6-21 (1:4) Sensitivity Analysis Ratios for Re-Review

These scenarios are realistic in that by shifting the design curve to the left and spending additional time upfront avoids the embedding of errors early resulting in a reduced chance for rework and a reduced time to re-review drawings. This occurs because of less embedded errors and the plan reviewers are familiar with the design drawings because they have been involved from the first major decisions of the facility.

Two scenarios where the reverse ratio occurs were also evaluated. The fourth scenario is a 2 to 1 ratio where the initial review results in a half reduction in the re-review. Therefore, twice the effort in the phased plan review process only results in half the reduction in rework percentage and re-reviews times. Table 6-22 and 6-22 show the category inputs.

| Variable | Initial | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ArchMu | 8.38 | 9.22 | 10.06 | 10.89 | 11.73 | 12.57 | 13.41 | 14.25 | 15.08 | 15.92 | 16.76 |
| ArchSD | 1.82 | 2.00 | 2.18 | 2.37 | 2.55 | 2.73 | 2.91 | 3.09 | 3.28 | 3.46 | 3.64 |
| StructMu | 21.50 | 23.65 | 25.80 | 27.95 | 30.10 | 32.25 | 34.40 | 36.55 | 38.70 | 40.85 | 43.00 |
| StructSD | 6.25 | 6.88 | 7.50 | 8.13 | 8.75 | 9.38 | 10.00 | 10.63 | 11.25 | 11.88 | 12.50 |
| MechMu | 10.90 | 11.99 | 13.08 | 14.17 | 15.26 | 16.35 | 17.44 | 18.53 | 19.62 | 20.71 | 21.80 |
| MechSD | 2.38 | 2.62 | 2.86 | 3.09 | 3.33 | 3.57 | 3.81 | 4.05 | 4.28 | 4.52 | 4.76 |
| ElectMu | 8.27 | 9.10 | 9.92 | 10.75 | 11.58 | 12.41 | 13.23 | 14.06 | 14.89 | 15.71 | 16.54 |
| ElectSD | 1.94 | 2.13 | 2.33 | 2.52 | 2.72 | 2.91 | 3.10 | 3.30 | 3.49 | 3.69 | 3.88 |
| FLSMu | 18.20 | 20.02 | 21.84 | 23.66 | 25.48 | 27.30 | 29.12 | 30.94 | 32.76 | 34.58 | 36.40 |
| FLSSD | 3.43 | 3.77 | 4.12 | 4.46 | 4.80 | 5.15 | 5.49 | 5.83 | 6.17 | 6.52 | 6.86 |

Table 6-22 (2:1) Sensitivity Analysis Ratios for First Review

| Variable | Initial | -5% | -10% | -15% | -20% | -25% | -30% | -35% | -40% | -45% | -50% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| r | 88 | 83.60 | 79.20 | 74.80 | 70.40 | 66.00 | 61.60 | 57.20 | 52.80 | 48.40 | 44.00 |
| ORewMu | 70 | 66.50 | 63.00 | 59.50 | 56.00 | 52.50 | 49.00 | 45.50 | 42.00 | 38.50 | 35.00 |
| RRevAMu | 4.05 | 3.85 | 3.65 | 3.44 | 3.24 | 3.04 | 2.84 | 2.63 | 2.43 | 2.23 | 2.03 |
| RRevASD | 1.53 | 1.45 | 1.38 | 1.30 | 1.22 | 1.15 | 1.07 | 0.99 | 0.92 | 0.84 | 0.77 |
| RRevSMu | 10.80 | 10.26 | 9.72 | 9.18 | 8.64 | 8.10 | 7.56 | 7.02 | 6.48 | 5.94 | 5.40 |
| RRevSSD | 2.90 | 2.76 | 2.61 | 2.47 | 2.32 | 2.18 | 2.03 | 1.89 | 1.74 | 1.60 | 1.45 |
| RRevMMu | 4.80 | 4.56 | 4.32 | 4.08 | 3.84 | 3.60 | 3.36 | 3.12 | 2.88 | 2.64 | 2.40 |
| RRevMSD | 1.51 | 1.43 | 1.36 | 1.28 | 1.21 | 1.13 | 1.06 | 0.98 | 0.91 | 0.83 | 0.76 |
| RRevEMu | 2.70 | 2.57 | 2.43 | 2.30 | 2.16 | 2.03 | 1.89 | 1.76 | 1.62 | 1.49 | 1.35 |
| RRevESD | 0.72 | 0.68 | 0.65 | 0.61 | 0.58 | 0.54 | 0.50 | 0.47 | 0.43 | 0.40 | 0.36 |
| RRevFMu | 7.60 | 7.22 | 6.84 | 6.46 | 6.08 | 5.70 | 5.32 | 4.94 | 4.56 | 4.18 | 3.80 |
| RRevFSD | 1.8 | 1.71 | 1.62 | 1.53 | 1.44 | 1.35 | 1.26 | 1.17 | 1.08 | 0.99 | 0.90 |

Table 6-23 (2:1) Sensitivity Analysis Ratios for Re-Review

The fifth scenario is a 4 to 1 ratio where the initial review results in a quarter reduction in the re-review. Therefore, four times the effort in the phased plan review process only results in a quarter reduction in rework percentage and re-review times. Table 6-24 and 6-25 show the category inputs.

| Variable | Initial | 20% | 40% | 60% | 80% | 99% |
|---|---|---|---|---|---|---|
| ArchMu | 8.38 | 10.06 | 11.73 | 13.41 | 15.08 | 16.76 |
| ArchSD | 1.82 | 2.18 | 2.55 | 2.91 | 3.28 | 3.64 |
| StructMu | 21.50 | 25.80 | 30.10 | 34.40 | 38.70 | 43.00 |
| StructSD | 6.25 | 7.50 | 8.75 | 10.00 | 11.25 | 12.50 |
| MechMu | 10.90 | 13.08 | 15.26 | 17.44 | 19.62 | 21.80 |
| MechSD | 2.38 | 2.86 | 3.33 | 3.81 | 4.28 | 4.76 |
| ElectMu | 8.27 | 9.92 | 11.58 | 13.23 | 14.89 | 16.54 |
| ElectSD | 1.94 | 2.33 | 2.72 | 3.10 | 3.49 | 3.88 |
| FLSMu | 18.20 | 21.84 | 25.48 | 29.12 | 32.76 | 36.40 |
| FLSSD | 3.43 | 4.12 | 4.80 | 5.49 | 6.17 | 6.86 |

Table 6-24 (4:1) Sensitivity Analysis Ratios for First Review

| Variable | Initial | -5% | -10% | -15% | -20% | -25% |
|---|---|---|---|---|---|---|
| r | 88 | 83.60 | 79.20 | 74.80 | 70.40 | 66.00 |
| ORewMu | 70 | 66.50 | 63.00 | 59.50 | 56.00 | 52.50 |
| RRevAMu | 4.05 | 3.85 | 3.65 | 3.44 | 3.24 | 3.04 |
| RRevASD | 1.53 | 1.45 | 1.38 | 1.30 | 1.22 | 1.15 |
| RRevSMu | 10.80 | 10.26 | 9.72 | 9.18 | 8.64 | 8.10 |
| RRevSSD | 2.90 | 2.76 | 2.61 | 2.47 | 2.32 | 2.18 |
| RRevMMu | 4.80 | 4.56 | 4.32 | 4.08 | 3.84 | 3.60 |
| RRevMSD | 1.51 | 1.43 | 1.36 | 1.28 | 1.21 | 1.13 |
| RRevEMu | 2.70 | 2.57 | 2.43 | 2.30 | 2.16 | 2.03 |
| RRevESD | 0.72 | 0.68 | 0.65 | 0.61 | 0.58 | 0.54 |
| RRevFMu | 7.60 | 7.22 | 6.84 | 6.46 | 6.08 | 5.70 |
| RRevFSD | 1.8 | 1.71 | 1.62 | 1.53 | 1.44 | 1.35 |

Table 6-25 (4:1) Sensitivity Analysis Ratios for Re-Review

### 6.10.1 Results

The results of the five sensitivity analysis are shown in figures 6-23 to 6-27. The first shows the figure resulting from the one to one (1:1) ratio.

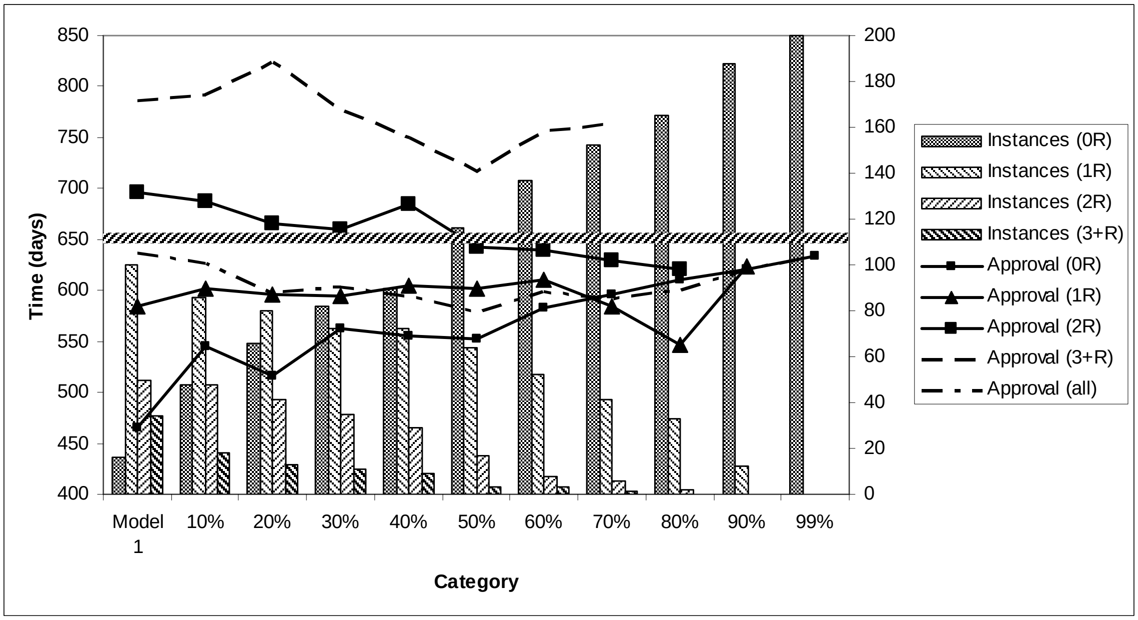



Figure 6-23 (1:1) Ratio Sensitivity Analysis

Here it can be seen that the overall time to permit remains about the same, however, an increase in predictability exists because the number of projects permitted with zero rework increases by six times, 20 instances to 120 instances. Increasing zero rework instances also reduces additional rework cycles. This reduces the amount of risk that the owner is exposed to by allowing them a better planning horizon to set their expectations to when the design drawings will be approved.

Figure 6-24 shows the second sensitivity analysis utilizing a one to two (1:2) ratio.

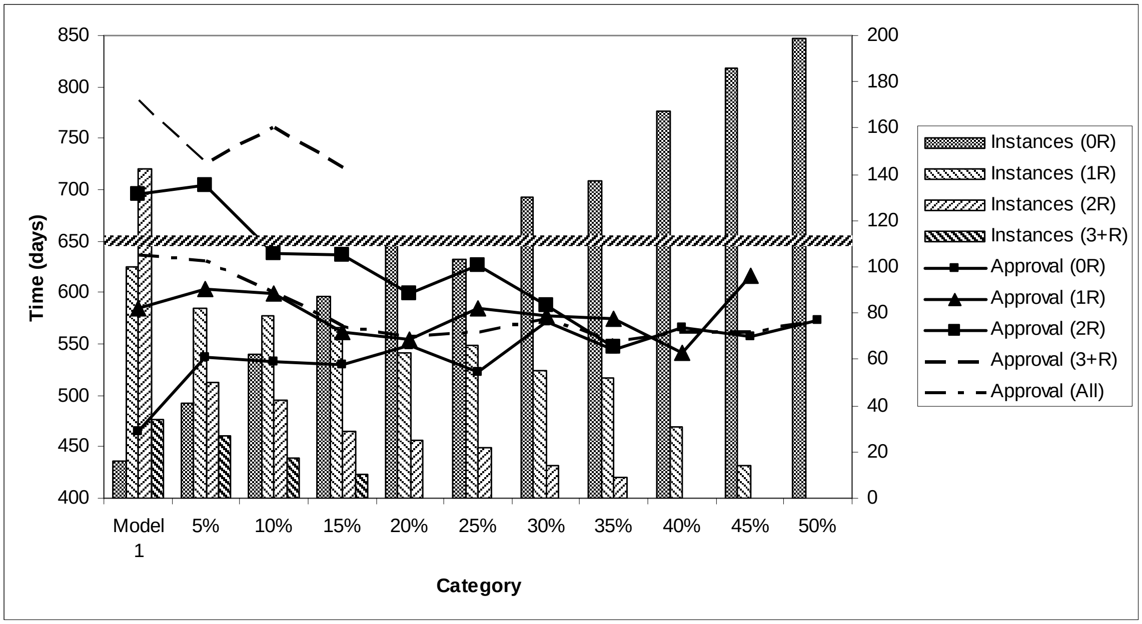



Figure 6-24 (1:2) Ratio Sensitivity Analysis

Figure 6-24 shows the mean time to permit of all projects decreases as the level of upfront effort reaches the 20% category but then shows diminished returns in the mean time to permit. However, with the increased upfront effort the system becomes more predictable with the number of projects requiring zero rework increasing linearly with each category. This result is expected and that no rework instances would occur at the 50% upfront effort because due to the double ratio, the chance for rework is zero. The biggest impacts to the time to permit occur with the two and three rework mean times to permit.

Figure 6-25 shows the opposite of a one to two relationship. It shows that the time to permit increases as the initial effort increases.

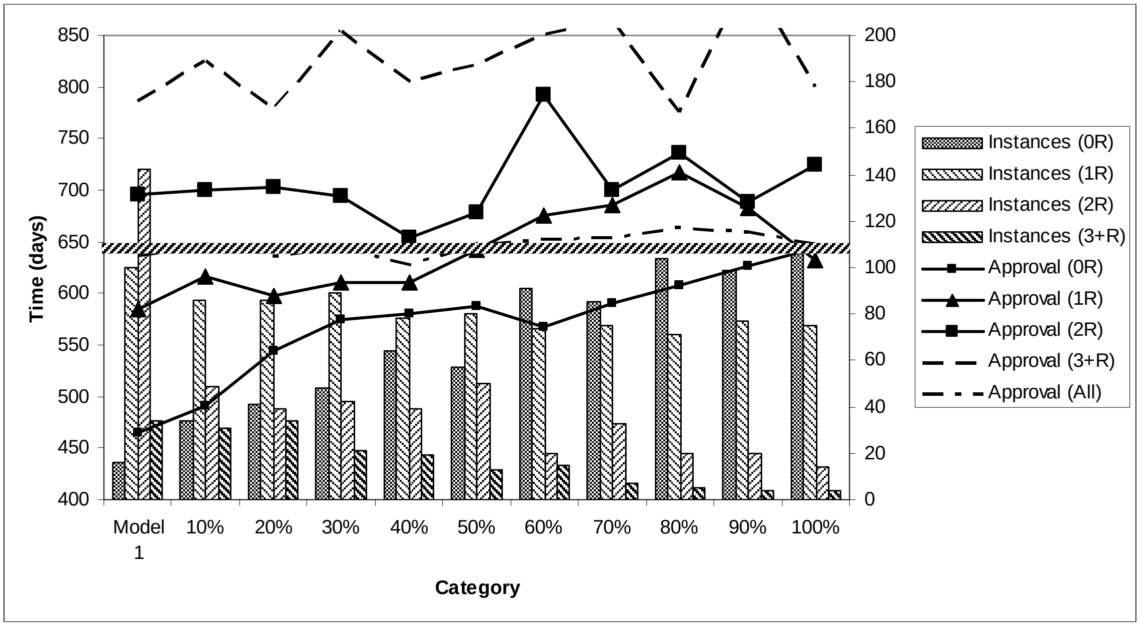



Figure 6-25 (2:1) Ratio Sensitivity Analysis

Figures 6-26 shows the third sensitivity analysis utilizing a one to four (1:4) ratio.

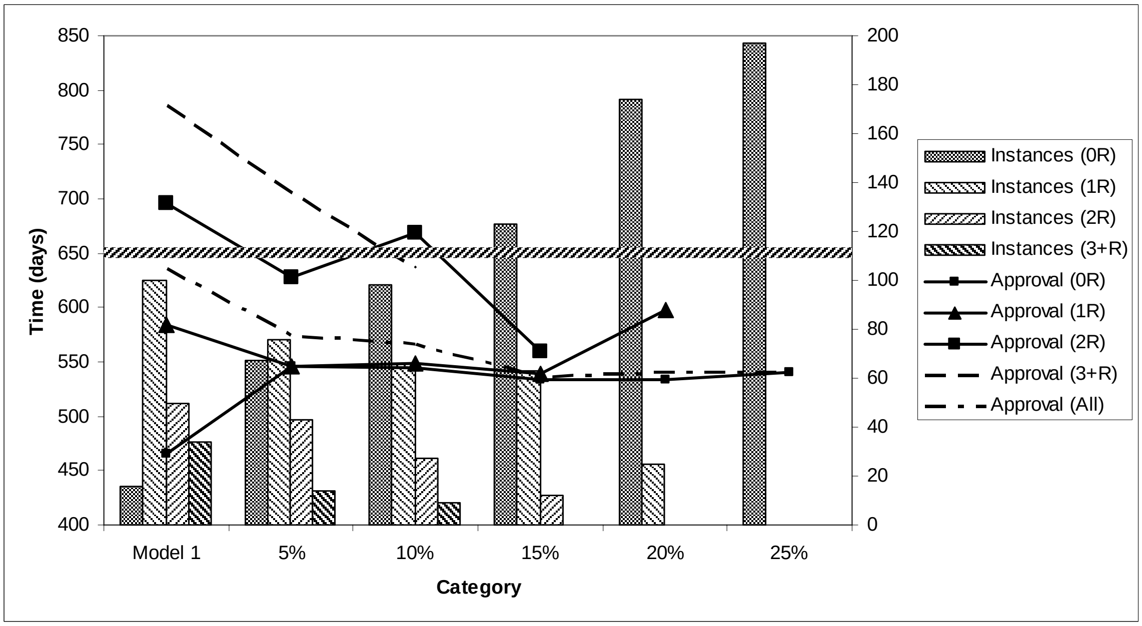



Figure 6-26 (1:4) Ratio Sensitivity Analysis

Figure 6-27 shows a four to one relationship where 20 percent increase in initial review effort results in only a 5 percent decrease in re-review times and rework rate. It shows that the overall time to permit increases and more points are above the 650 days to permit line that is consistent in figure 6-25.

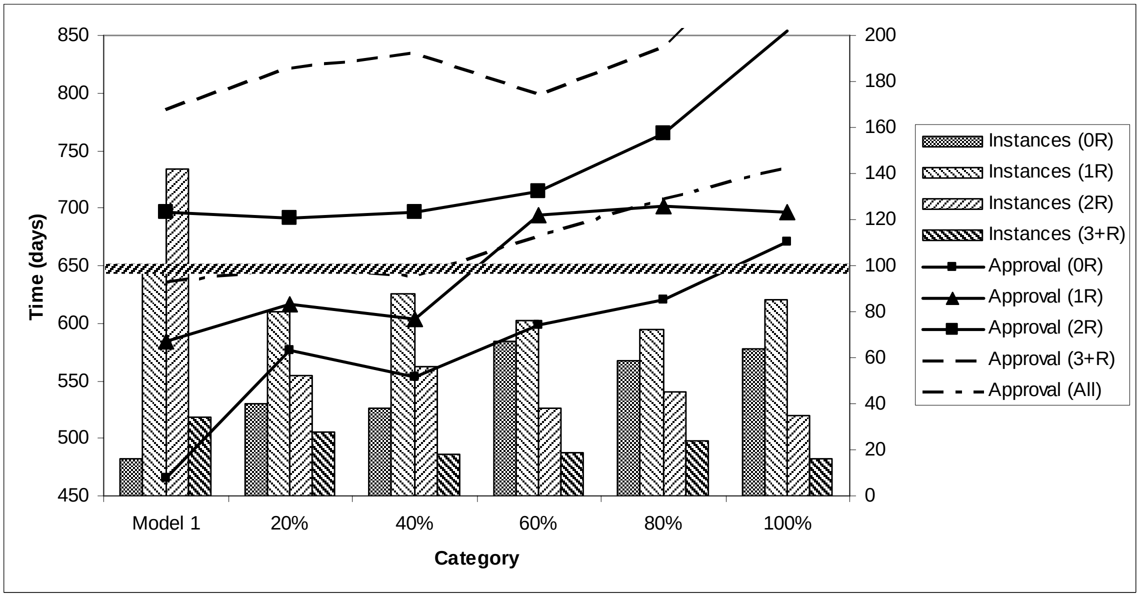



Figure 6-27 (4:1) Ratio Sensitivity Analysis

Three scenarios were conducted to determine the impact of an alternative review process. Projects are placed into four categories and entered into the simulation model. The original model represents the current organizational process receives approximately 50 category I projects, 100 category II, 35 category III, and 20 category IV projects in a six month time frame. The second and third scenarios focused on a dedicated team to perform alternative review only. This was a request by the Facilities Development Division which intends to put this team into practice and wanted to know the impact to the mean time to permit for the largest projects that the organization encounters. These two scenarios of a dedicated alternative review process were loaded with 40 and 50 category IV projects and are referred to as DA40 and DA50 respectively.

Figure 6-28 shows normal distributions for three simulation scenarios. From left to right the first two represent a dedicated review team that only performs an alternative review process (40 and 50 projects respectively). The third curve represents the time to permit for the original organizational structure (20 projects). Each scenario utilized a sample size of 1,000 simulations.

The decreased mean time to permit represents only a portion of the benefits of an alternative review process that engages major stakeholders early. Additional benefits of the alternative review process include (1) reduced probability of rework, (2) if rework does occur, the time to correct, resubmit and re-review is reduced, and (3) increased job satisfaction for the plan reviewers. Increased job satisfaction occurs because the plan reviewers are now integral members of a design team and are involved in a proactive process to design a healthcare facility versus the reactive process where they constantly catch design errors.

I performed a statistical analysis to compare DA40 and DA50 with the original mean time to permit. DA40 (mean 450 days, SD 192) and DA50 (mean 530 days, SD 212) were compared to the original model (mean 650 days, SD 181) resulting in a p-value of 0.0001 for both scenarios.

This research and supporting simulation results recommends utilizing a separate review team to handle alternative review projects resulting in an overall mean time to permit savings of approximately six months. However, this dedicated review team should maintain a threshold of 40 to 50 projects in its queue, otherwise, diminishing returns on the mean time to permit occurs.

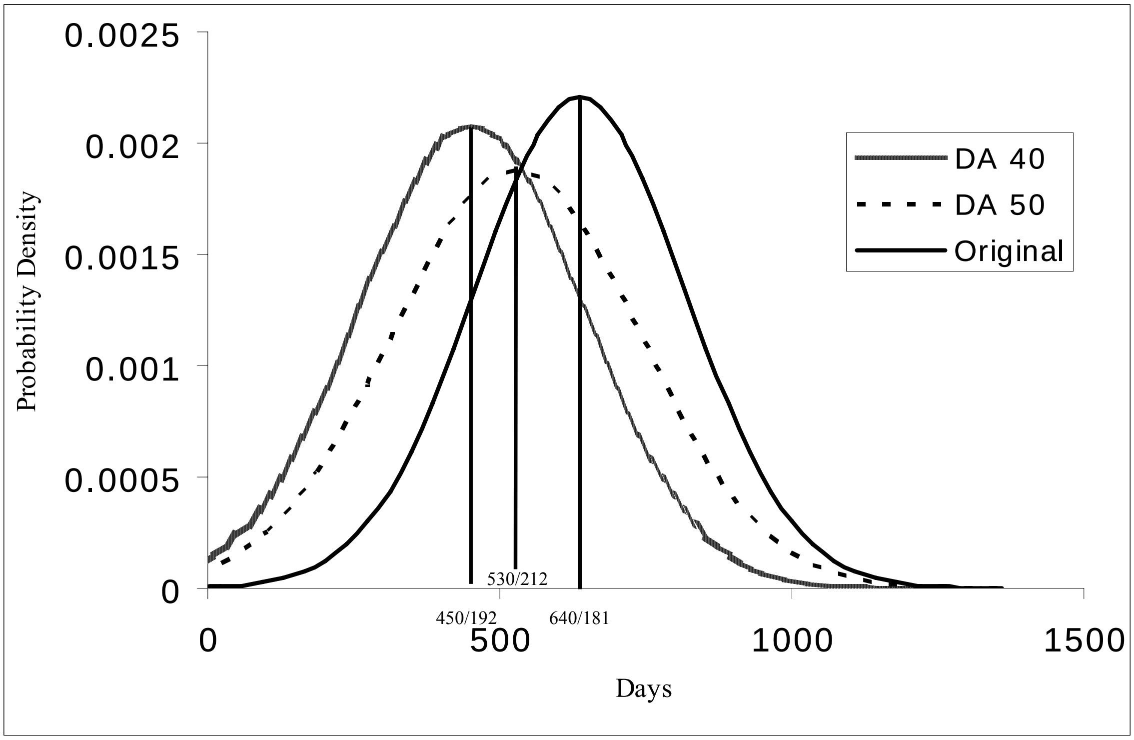



Figure 6-28 Mean Time to Permit for Three Scenarios (N = 1000)

Figure 6-29 shows mean time and stability. Along the x-axis is a series of projects from three sources. The first two series of projects compile the mean time to permit obtained from simulations runs of a dedicated review team loaded with 40 and 50 projects. The third series of projects compile the mean time to permit from the FDD database. These times are individually plotted with the time to permit on the y-axis. This graph shows a reduction in the mean time to permit as well as more stability and predictability due to a dedicated alternative review team. The FDD project mean time to permit is approximately 610 days with a standard deviation of 390 days indicating large variation in the time to permit.

While the simulation data shows a reduced mean time to permit of 450 days and a reduced standard deviation of 190 days an improvement of 25% permitting time and 50% improvement in standard deviation. The 50 project simulation data shows a reduced mean time to permit of 530 days and a reduced standard deviation of 210 days an improvement of 13% permitting time and 26% improvement in standard deviation.

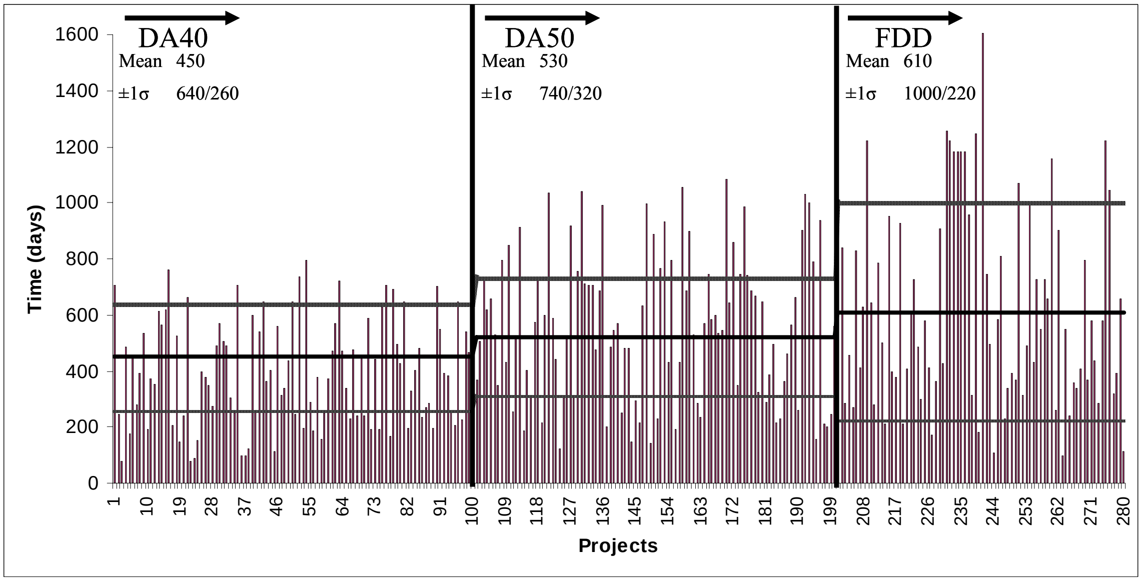



Figure 6-29 Mean Time to Permit for FDD and Simulation data

I realize the number of personnel increases in the system, but it is the organizational makeup that makes the difference here. Politically, the organization receives a lot of attention for those large projects and to be able to save six months of cost escalation will prove very beneficial to the organization in terms of providing the best customer service to their constituents. In turn, this will help the organization politically because less interest will come from the state politicians.

Realizing that system behavior can affect the largest project category's mean time to permit, another model was conducted to evaluate system behavior. This scenario reduced categories one, two and three by a series of percentages ranging from 10% to 50%. The fourth category implemented an alternative review process utilizing a 30% increase in initial effort resulting in a 30% decrease in category rework and re-review time. Figure 6-30 shows the result of this scenario.

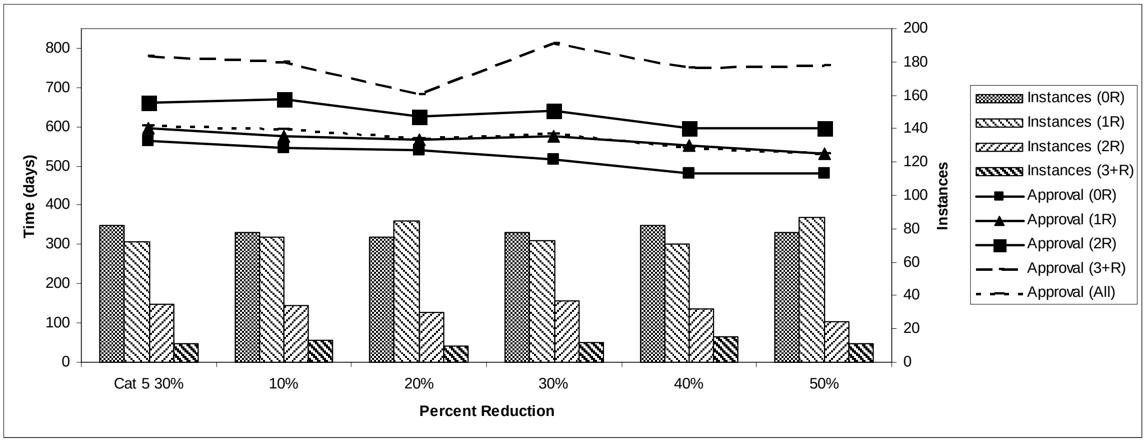



Figure 6-30 Other Category Rework Reduction with Category IV at 30% Effort Level

In general each of the mean times to permit for category IV are reduced due to less rework in categories one, two, and three. This is expected decrease in mean time to permit for category IV occurs because the plan reviewers have less overall work because they do not have to deal with rework situations in categories one, two, and three.

The number of rework instances for category IV is expected to remain constant because category IV rework percentages remains the same. More system behavior confidence is realized due to expected results.

6.10.2 Limitations

Four limitations are identified for research in discrete event simulations.

1. Simulating an organization using a discrete event simulation is difficult because modeling human behavior is complex. Understanding human capabilities through simulation alone can not solve problems (Chung 2004).
2. Organizations change over time, they can exist in different formats from functional to matrix to project specific models and the data retrieved from the organization is a

historical picture in time. Change occurs because people in an organization get fired, retire or move on and new personnel are hired. The change of personnel can significantly influence how the organization behaves.

3. A large database has been obtained that measures the workflow through the organization; some of the data may not be reliable. Data is only as reliable as the people that input the information. Therefore some of the data is inaccurate. In some instances, projects were closed out as finished when in reality they were not complete. This data will be removed from the simulation analysis.
4. OSHPD is a unique organization primarily staffed with architects and engineers which may make it difficult to apply findings to another organization.

### 6.10.3 Validation through Interviews

The work completed in case study II was validated through an in-depth interview and presentation to the Deputy Director of the Facility Development Division. Qualitative validations for four points are discussed next.

The high rework rate calculated for the four model categories required validation since each category had a rework rate above 85%. I was concerned if this adequately represented what occurs with drawings reviewed by the FDD. The deputy director confirmed that the rework rates were accurate and he expected the rework rates to be higher than what I had calculated.

In two additional interviews with regional plan supervisors the high rework rates were accurate. Both supervisors agreed the rework rate is above 85% for all categories and one stated "it is a very rare occurrence that a set of drawings are approved the first time (Ring 2008)."

The dynamic rework cycle required validation because the simulation model allows projects to be reworked indefinitely, in which the deputy director stated "That is for sure! (sarcastic tone) (Gillengerten 2008)." He inquired about the number of rework cycles that typically occur in the computer simulation. I responded with, "it is rare that a project is reworked more than four or five times." The deputy director agreed with this statement and has a policy, that once drawings reach the fourth rework cycle, "I call the owner and design team and explain that their project is in jeopardy of being rejected entirely from the review process so it is a good thing that the computer model does not have more than three or four rework cycles (Gillengerten 2008)."

Plan review times required validation to accurately model system behavior. The deputy director agreed that review times increase with larger categories of work and that the structural and fire, life, and safety reviews take the longest. He has always believed that structural and fire, life, and safety reviews were the longest and that it was good to see the data from his database supported that notion.

Ultimately, the deputy director believed that the computer simulation accurately showed the system behavior of his organization and closed with the statement that this research effort helps him "manage by fact (Gillengerten 2008)."

I identified two limitations through validation interviews.

1. Small sample size does not allow for a quantitative analysis, therefore the validation process must be accomplished through in depth interviews. To address this limitation

multiple interviews were conducted with three leaders within the organization to understand their opinions about the results of the computer model.

2. Biased answers from the interviewees because they have a vested interest in the organization. Also, the interviewees may be biased because they have worked with the researcher and may report only the positives of the research accomplished. To address this limitation, I ensured that the simulation model was created and analyzed from existing data on the organization so they would feel free to comment openly and honestly on the work.

## 6.11 Industry Questionnaire

I developed with input from OSHPD regulators, owners, architects, engineers and contractors to explore the characteristics necessary to succeed in mitigating rework within the healthcare facility construction industry. A series of in depth interviews were conducted to develop thirteen questions owners and design teams should reflect on prior to engaging OSHPD in a new process of alternative review.

1. Do you have design phase schedule? It is imperative to detail on the design activities to understand the handoffs of information to each discipline engineer.
2. Is your project going to be reviewed in house or third party contract review? In house review by OSHPD has an impact because the reviewers are required to review other work and may not have the ability to dedicate as much time to the review. While, a third party contract review will be able to allocate more reviewers based on the needs of the project schedule because they sign a contract to provide information on a scheduled basis.

3. Are you willing to adopt integrated project delivery teams, lean, BIM? The members interviewed believe it is imperative to adopt integrated project delivery teams, lean and BIM to be successful in using an alternative review process. The alternative review process requires coordination between owners, designers and contractors to understand how the facility is constructed and using BIM readily facilitates the process.
4. Do you have contractors on board, which ones and describe their breadth of responsibility? If not, when will they be brought on and what is expected of them? Without contractors on board early, uncertainty increases in whether the design can be constructed and what the costs of the design is. Also, just having them on to do costing is not enough; contractors must work with designers and owners to incorporate the process of installation with the products that will be used.
5. Have members of your team received the informational session on phased plan review? The healthcare facility industry along with state regulators developed an informational session on the specifics to alternative review process. Receiving the information presented in the forums give industry members direct insight into how the alternative review process works.
6. Is an expectations matrix established? An expectations matrix details out the information that the design team must provide at each phase of the alternative review process. The matrix makes it explicit what is to be provided and what is to be reviewed.

7. Can you provide a description of how the design team will involve owners in decision making both operational and budget? Owners have an impact on project delivery and therefore is an important to reducing variability in the decision making process. How many owners will be addressed and who makes the final decision is important to ask prior to beginning the design process.
8. Can you present a methodology on team decision making? This question details out how the design team will make decisions on major issues. Are decisions made by consensus or does the owner have final say. What tools will be used to make educated decisions.
9. Is the owner willing to self certify the budget for the facility that it can meet future construction costs, fees, and entitlements? This question makes the owners think about their business plans in depth to ensure that they have captured all possibilities that may affect the project budget.
10. Is the owner willing to self certify the space utilization plan for the facility? Change in floor plans and space use is a source of cost increase. Therefore, limiting the changes is necessary to utilize the alternative review process.
11. Is the owner willing to self certify that the program for the facility is closed and will not be reopened? This requires the owner to keep the business plan closed once it is determined. Changing what services to provide mid-stream through the design will prove detrimental to the alternative review process. Most likely, the project will not be able to proceed through the alternative review process and will resort back to the standard of providing 100% contract drawings for review by the regulators.

12. Are you able to present which items you believe will require peer review or alternate means of compliance? Identifying items that will require additional peer review and alternate means of compliance is imperative because they are long lead items and require agencies outside of OSHPD to help in the decision making. Thinking about this ahead of time can keep the project going in an alternative review process.
13. If your firm is not familiar with OSHPD procedures, are you willing to partner with a firm that has experience with OSHPD permitting processes? Gaining experience and help from another firm will improve the design process pursuing alternative review and having projects that do not flow through efficiently is detrimental to the entire system. The permitting process is complex and therefore partnering with an experienced firm will greatly enhance the success of the project.

## 6.12 Section Acknowledgments

I would like to thank the members at OSHPD for their insight, without their help, this work would have never occurred.

# 7. CONCLUSIONS

In this dissertation research I show that many causes of rework exist in the design and permitting phase of a healthcare facility. I show that negative rework is detrimental to system performance and I identify three throttles that impact production systems, each one having a varying degree of control. One controllable throttle to a production system is the amount of rework that is developed during the design and construction phase. I show that reducing rework increases capacity, reduces variation, and leads to system stability. I also show, qualitatively, that a better permitting process increases worker satisfaction.

To improve the design and permitting process, we must break free from traditional project roles, where information is isolated and protected, and move to an environment where we understand the workflow of others, which leads to process improvement. We should make every effort to shift the design curve to the left by working in an integrated and collaborative environment. We should seek to eliminate rework and if necessary reduce rework as far upstream as possible.

In section 7.1, I discuss management suggestions for healthcare facility design resulting from this research. In section 7.2, I consolidate the limitations of my research and answer the research questions I posed in chapter 1. In section 7.3, I discuss the academic contributions of my research and in section 7.4, I discuss future research questions.

## 7.1 Management Suggestions

I present the following management suggestions to reduce or eliminate negative rework that occurs in healthcare facility design and permitting.

1. Owners could request that the design team implement a built-in quality process to eliminate errors in design as far upstream as possible. This can enhanced by a phased plan review process, as has been adopted by OSHPD, which allows early involvement of its plan reviewers in the design of the healthcare facility. Previously, regulatory reviewers were allowed to perform only a cursory preliminary review of healthcare facility designs and had to wait until designs were submitted as 100% designs. Presumably, this resulted in a high probability of errors being embedded early in design because OSHPD could comment on them only when they had received the drawings for review. OSHPD was seen as a quality control agent, when in fact, their sole responsibility is to ensure healthcare facility designs meet code requirements.
2. Owners could request the design team to use building information modeling (BIM) to aid in the communication of facility requirements. Ensuring that all project participants are working off the latest design information by utilizing building information modeling reduces the delay when changes to the design are made. Furthermore, by using BIM, these changes to the design are made transparent to all project participants which reduces confusion and interdisciplinary design conflicts.
3. Owners could perform business case scenarios to ensure the proposed facility can meet all of their needs. One way of performing a business case scenario is to use a target costing process. Target costing begins with setting a target price during the owner's plan validation phase. A target margin is subtracted from the target price.

The target price minus the target margin equals the target cost. One important tenet of target costing is: if the target cost cannot be met, then the facility should not be constructed (Clifton et al. 2004). For more information on target costing see Ballard and Rybkowski (2009), and Nicolini et al. (2000).

4. Design teams could use reverse phase scheduling to appropriately allocate resources to specific design requirements. Reverse phase scheduling starts with the end date in mind. In California healthcare facilities, this date is typically the desired date of occupancy. From there, the schedule is worked backward to include construction, permitting and review, and design. Reverse phase scheduling requires an integrated team to provide inputs on the entire series of events.
5. Better definition of handoffs for design information, owner requirements, and design review requirements should be established. This can be enhanced by using a design structure matrix (DSM). DSM provides the design team a way of understanding how inter-related tasks impact each other. It also provides a simple, compact, and visual representation of a complex system that supports innovative solutions to decomposition and integration problems (Browning 2001). Further discussion of DSM is outside the scope of this research. For more information on DSM see e.g., Tuholski (2008), Tuholski and Tommelein (2008, 2009), Crawley and Colson (2007), and Maheswari et al. (2006).
6. Design teams could implement a production control system which reduces process variability and promotes reliable promising. A system that provides metrics to measure production performance in the course of process execution is highly recommended. One such system is the Last Planner™ (Ballard 2000).

7. The owner, design team, and contractors could implement a relational form of contract which allows monetary funds to cross organizational boundaries in search of the best possible solution. One such contract is the Integrated Form of Agreement (IFOA).
8. Design teams could enter into a collaborative review process when submitting large drawing documents to a state permitting agency. This review should involve all major stakeholders and a process defined on how interactions will occur between the design and review teams. This could also include defining what areas of the design will be reviewed as the design evolves. Clearly stating deliverables on what is and what is not approved on the drawings, and how each discipline will be reviewed, are vital. Will the structural portion be a true phased and approved review? Will the other disciplines (electrical, mechanical, architecture, and fire, life, and safety) be an evolving review where design alternatives are agreed upon but not formally approved until the entire system is designed. This research indeed recommends the latter.
9. Design teams could implement a set based design strategy to bring more alternatives further down the line in the development process. Then, when enough information presents itself, alternatives are eliminated. The benefit of this strategy is that more information is developed for the entire design process. Also, selecting a single alternative early in the process can introduce large amounts of negative rework if the alternative is deemed infeasible. For further information on set based design see Parrish (2009), Parrish et al. (2008), Ward (2007), Sobek et al. (1999), and Ward et al. (1995).

These management suggestions outline approaches that are already being taken separately and in combination by “experimental” projects. It is clear that the industry is finding ways to improve performance. It is in this context that this dissertation research makes its contributions to industry.

## 7.2 Research Findings

Figure 7-1 shows a consolidated picture of the research presented in chapters 3, 4, 5 and 6. The taxonomy of rework in chapter 3 provides a reason to study rework and its impact on production systems. Chapter 4 describes a real world production system that is affected by rework and a simulation model is used to demonstrate how a mechanical contractor can deal with changes timing. The research presented in chapter 4 focuses on the construction phase of a project and does not attempt to address rework that occurs in the design phase. Chapter 5 analyzes a simple rework process to build intuition on three throttles that can affect a production process. The production process is a simplified version of a review agency and shows how resource capacity is affected by variation. The research presented in chapter 5 focuses on the design phase of a construction project and does not extend to the construction phase. Chapter 6 builds on chapter 5 by adding complexity and field data into a simulation model to determine how an alternative review process can improve a production process. This alternative review process builds quality in the production system in an effort to eliminate rework. The research presented in chapter 6 focuses on the review and permitting process of the design phase and does not extend to the construction phase.

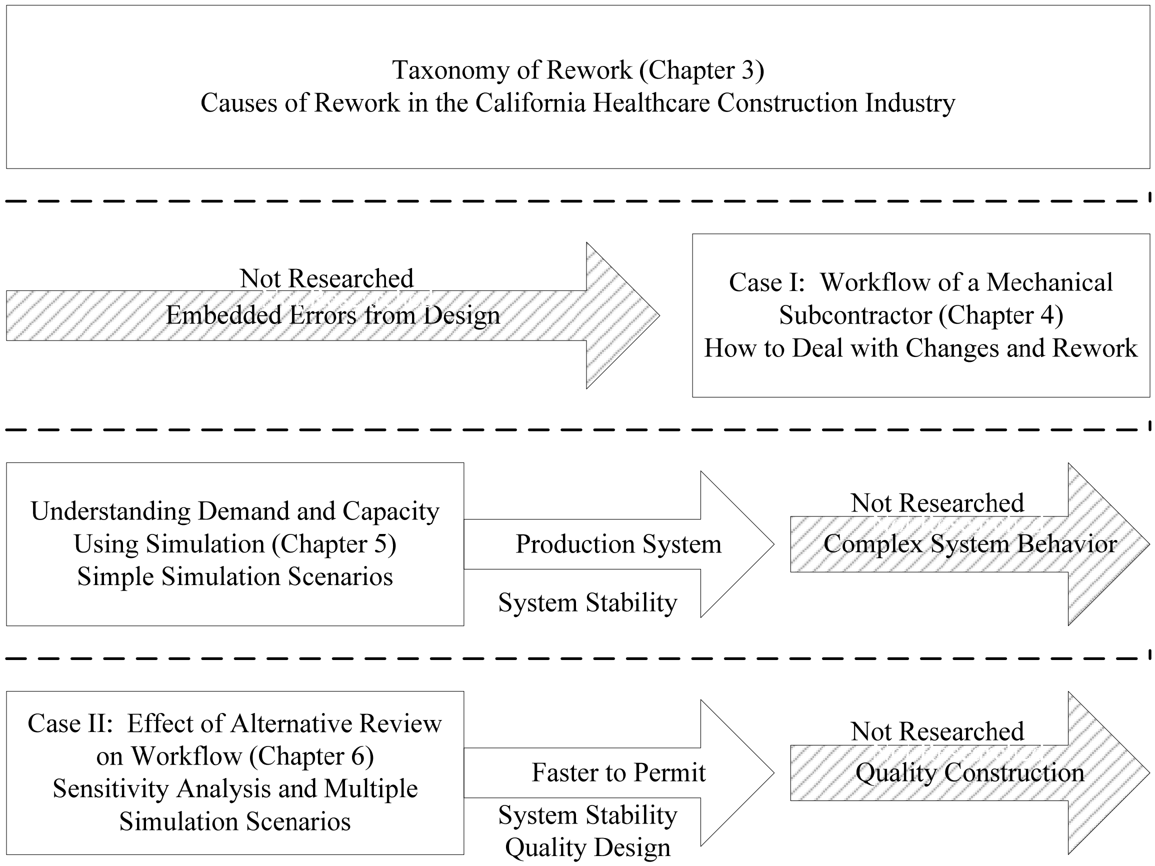



Figure 7-1 Consolidated Research

The rest of section 7.2 will answer the research questions I posed in chapter 1.

**Research question 1:** What are the root causes of rework in the healthcare facility construction industry?

I placed the root causes of rework, as discussed in chapter 3, into three categories: (1) design, planning, and scheduling, (2) design review, and (3) planning, programming, and budgeting. Items were classified into discrete categories, however, I recognize that the causes of rework may not be mutually exclusive. The categorization process remains useful because it creates a reference point from which further discussions on process improvement can take place. I found that the majority of rework causes are due to the design, planning, and scheduling of the design effort. The research presented in chapter 3 suggests that an alternative review process can eliminate many causes of negative rework that occur in the design, planning, and scheduling phase. This alternative review process, which engages all stakeholders early to avoid negative rework, is discussed further in chapter 6.

**Research Question 2:** What strategy should a mechanical contractor adopt to avoid negative rework during the construction phase?

My research suggests that a mechanical contractor in light of late design changes should adopt a delayed management strategy which is to wait to detail and fabricate items until the last responsible moment. In case study I, the last responsible moment is to make the changes in the field. This includes replacing items that had already been installed. A delayed management strategy fits this scenario because the mechanical contractor experienced variation when management tried to identify all changes occurring in the detailing phase. Trying to identify all changes in the detailing phase caused confusion throughout the organization because interdependence exists between detailing, released drawings, on-site edits to drawings, and version control of drawings. Management discovered if changes were allowed to flow to the construction site, the on-site personnel could best determine the change which reduced workflow variation.

A delayed management strategy benefits the mechanical contractor because changes become very clear to everyone involved when they occur. Another benefit is the ease of determining the cost impact of the change, which in turn makes the cost clear to the general contractor and facility owner. Also, the mechanical contractor does not get reimbursed for work that is 'done behind the scenes', such as correcting deficient drawings and accommodating design changes. Finally, by following this delayed management strategy, the detailers' motivation and productivity increased because they did not have to stop work on current production to re-detail drawings that had incomplete information.

**Research Question 3:** What are the throttles on a simple design review process and how are they controlled?

I identified and modeled three throttles in chapter 5 that impact the design review process. The three throttles are (1) inflow of projects, (2) review capacity, and (3) likelihood of rework. The first throttle is difficult to control by the review organization because it is affected by political and economic forces. Politically, the inflow of projects is affected, e.g., by mandated facility upgrades to meet seismic requirements. Economic forces affect the inflow of projects because of service demand. Service demand is created by population requirements for medical care. The second throttle can be controlled by the review agency and my computer model shows that an increase in resource capacity is required to compensate for high rework percentages. The third throttle is affected by the quality of drawings submitted to the review agency. My computer simulation shows that the time to permit and the resources required to stabilize the system decrease if the likelihood of rework remains low. Therefore, it is necessary to develop alternative review processes that eliminate negative rework.

**Research Question 4:** What is revealed from a sensitivity analysis conducted on a plan review simulation?

The sensitivity analysis on the review and re-review times on a plan review simulation in chapter 6 shows that the time to permit can be improved if an alternative review process is implemented. As modeled, this improvement is directly tied to the amount of upfront effort invested as long as the return on the investment decreases the rework rate and the re-review times. The rework rate and re-review times get reduced because errors are eliminated from the design due to upfront collaboration between design engineers and the plan review agency. Simulation of a dedicated team to perform an alternative review process showed a statistical improvement over the current process for reviewing category IV projects. An alternative review process requires more upfront involvement of owners, designers, contractors, and regulators to avoid the embedding of errors into the design drawings. An alternative process can result in fewer errors at the final review of the drawings, thereby expediting the time to permit.

**Research Question 5:** How can a plan review system be stabilized for mean time to permit and improve predictability?

I show in chapter 6 (figures 6-28 and 6-29) from my computer simulation that implementing a dedicated review team for category IV projects stabilizes the mean time to permit and improves the predictability of when individual projects will be approved. Due to reduced rework rates, the instances of rework decreases, which gives healthcare owners more predictability of when their projects would be approved and permitted.

**Research Question 6:** How can errors in healthcare facility design be detected and corrected?

This research and literature suggests that if an error is present, the error is more easily corrected when the design curve is shifted left because the design professionals and plan reviewers have a greater shared understanding of the project and can quickly resolve ambiguities and misconceptions. Also, the chance is reduced of discovering a very large error that may require the entire project to be redesigned. Major errors are identified and corrected early on in the process where the design team has adequate time to correct them which eliminates the cascading effect of the error. For example, if the exiting plan for fire, life, safety is not adequate and this error is allowed to continue down the line, it would ultimately affect the floor layout, structural, mechanical, and electrical designs. However, when the error is avoided to begin with, the chance of a cascading error is eliminated.

This alternative review process allows the plan review agency to be more familiar with the designer's intent. Since the plan reviewer is allowed to participate early on in the design, the design does not have to be explained to the plan reviewer during the final permit review. For example, the plan reviewer understands the intent of the exiting plan which details the flow of personnel during an emergency.

**Research Question 7:** What is the effect on the plan review agency if benefits from an alternative review process are not realized?

If benefits from an alternative review process should not pan out, i.e, initial plan review investment, do not reduce the rework rate and re-review times, the time to permit increases dramatically. Figures 6-25 and 6-27 illustrate the increased time to permit. The increased time to permit occurs because of constrained system resources (i.e., one discipline reviewer), if the plan reviewer spends more time on the initial review and the rework rate still remains high, then other projects are not being reviewed and remain in the system longer, increasing the time to permit for all projects.

If more time is spent upfront on plan review and negative rework is not reduced, the entire system suffers, the backlog of projects will continue to grow, and projects will take a longer time to permit as shown in chapters 5 and 6. For example, if the alternative review process is followed, but the owner makes dramatic changes to the drawings before the final submittal, the chance that rework will be required is very high and the upfront time spent on reviews by the regulatory agency will largely be wasted.

If this scenario occurs, the plan reviewers will be de-motivated because trust within the system will be broken. A major piece that must be present for an alternative review process to work is trust, i.e., trust that designers will not change items that have been previously agreed upon. If this trust is broken, cascading effects occur throughout the system: the plan reviewers will become skeptical of the process and may not continue to put their best effort forward to follow through with the alternative review process.

**Research Question 8:** What strategy should a plan review agency adopt to avoid negative rework during the design and permitting phase?

My research suggests that a plan review agency should adopt an alterative review process that requires early involvement of plan reviewers, owners, architects, designers and contractors during the permitting phase of a healthcare facility. Quantitatively in chapter 6, I show that an alternative review process can decrease the mean and standard deviation of the time to permit healthcare designs. A reduction in the mean time to permit occurs because the alternative review process improves the design and permitting effort. This alternative review process allows the shared understanding of the project to be obtained earlier by all project stakeholders which reduces or eliminates negative rework.

## 7.3 Contributions to Knowledge

### 7.3.1 Taxonomy of Rework Contributions

Extending an existing taxonomy of rework where necessary provides a qualitative insight on where rework occurs in the design and permitting of healthcare facilities in California. Understanding where the causes of rework occur provides a basis for where management can improve the process. In this research, a substantial portion of rework occurs in the interaction between the design team and the regulators. In the current process, design errors occur early because design teams do not interact with the regulators; this situation creates a large source of negative rework when the errors are discovered.

This work utilizes root cause analysis by collecting information from a variety of sources and determining causes of rework. Root cause analysis can provide design teams with a clearer picture of what causes the permitting process to be inefficient.

This research highlights that all stakeholders within the design and construction of healthcare facilities in California have a part to play in improving the current permitting process. In many situations, people understand that the current process is not efficient, but they do not have or take the time to step back and analyze the causes, instead, they end up pointing fingers at what is wrong and at others. Consolidating and distributing this research is a valuable academic contribution that enables industry members to tightly couple learning with action.

### 7.3.2 Case I Contributions

Developing a discrete event simulation model of workflow of a mechanical contractor provides both qualitative and quantitative insight on how an organization can change their process to deal with unmanaged variation. As previously mentioned, unraveling the interrelatedness between design detailing, fabrication, and installation provides insight into design and construction management theory. This research provides a systematic process on how to deal with upstream variation due to designs that continually change.

This case study supports previous research that contends that detailing and fabrication can be delayed because of their respective speeds of production. Detailing and fabrication can be accomplished relatively quickly which provides the mechanical contractor time to keep up with the construction schedule by waiting for more complete design information. This management strategy supports the idea of the last responsible moment where one waits to make a decision until the time where an important alternative is eliminated if a decision is not made. The ability to delay detailing and fabrication for more complete information can be increased by reducing production lead times for detailing, fabrication, and installation. This management strategy provides a framework to reduce process variation.

### 7.3.3 Understanding Demand and Capacity Using Simulation Contributions

The discrete event simulation presented in chapter 5 provides an intuitive and simple way of understanding the impact rework has on a production system. The concepts of controlling the three throttles to a production system (inflow, production capacity, and likelihood of rework) can be widely applied to other production systems. It provides more evidence that developing a culture where errors are not acceptable can dramatically improve production system performance.

Understanding the interaction between demand and capacity highlights the need to develop a management strategy that can balance the two. Management must understand that upstream work directly affects their resource allocation. Providing a collaborative environment where errors are eliminated from upstream work can significantly reduce resource demand. This research demonstrates the need to reduce process and product variation.

### 7.3.4 Case II Contributions

Case study II provides a proof of concept for a discrete event simulation model that takes OSHPD data and constructs a model of how healthcare facility permitting projects flow through plan review time gates and how much rework is necessary.

The case study further shows the impact of an alternative review process through a discrete event simulation model. This research adds to the body of research of computer simulations that model existing organizational processes in an effort to understand organizational workflow. The simulation makes a change to an organizational process and illustrates the impact of the change against existing organizational data.

Design firms can understand a submission strategy for design drawings that will improve their approval times. Providing insight to different submission strategies can improve system performance.

This research provides a deeper understanding of the impact that various types of work have on a review agency. Due to system behavior, changes to one category of work impacts other categories of work. This idea can be applied to any organization that encounters variation in their workflow.

This work provides an understanding of the challenges to implementing alternative review processes within a plan review agency. Senior leaders of the organization expressed caution and skepticism to adopt a different process due to the uncertainty of whether or not the new process will make an improvement. This is a major hurdle in adopting any new process. However, conducting computer simulation analysis of the process change, gives confidence to the organization that a change can improve the process.

Case study II reveals the impact an alternative review process can have on the regulatory agency and the design community. The simulations of the alternative review process show a dramatic effect on the time to permit a California healthcare facility. The original design process is quite isolated for the design engineers; whereas an alternative review process is much more collaborative. However, new operating procedures have to be followed and many designers realize that the old paradigms of designing and then throwing information over the wall will not work in this alternative review process.

## 7.4 Future Research

I raise the following future research questions.

**Question 1.** How does implementing a chief engineer who would understand owner needs and then conveys those needs to the design team impact the permitting process? Womack and Shook (2006) state the chief engineer is the most important person in an organization because he/she listens to the owner and then determines what the organization need to do to address owner's needs. In construction, multiple tiers of needs exist for a facility. At one level, the design team needs to know the overall function of the building. At another level, the design team needs to know specific details from groups of owner representatives. For example, at a high level, a healthcare facility will support 200 beds and 10 surgical rooms. At a lower level, each discipline engineer must meet with owner representatives to determine the specific needs to support the overall need for the facility. Traditionally, each discipline engineer is left on their own to determine what are the owner needs and then the discipline engineers have to come together to address the conflicts. In contrast, a chief engineer would understand both the high and low level needs for all disciplines and balance those against what is feasible both technically and economically. In this scenario, the chief engineer would also understand the concerns of the regulatory agency and be able to convey their needs to the discipline engineers. This would alleviate continuity and misinformation issues that arise during traditional project reviews. However, very few individuals are trained to understand architectural, structural, mechanical, electrical engineering and all the other disciplines needed to construct a healthcare facility. AEC practitioners have not traditionally used chief engineers, but opportunities exist to develop people in this role.

**Question 2.** How does assigning rework to multiple disciplines affect the permitting process? Currently the simulation model described in chapter 6 assigns one discipline error during each rework cycle. However, multiple errors can be embedded simultaneously into each rework cycle. For instance, a required change in fire, life, and safety requires a change in the structural, mechanical, and electrical layouts. If the exiting plan has to change the layout of the floor plan, the mechanical and electrical systems may have to be moved. At the very least, the systems have to be rechecked, which requires the drawing set to return to those discipline reviewers. This recheck would increase the time to review drawings through the various disciplines and this, in turn, would increase the time to permit. While the current model reasonably predicts the time to permit a drawing set, adding multiple discipline errors may shed further light on the overall process. By adding this to the model, it may be possible with more data from OSHPD to understand which discipline affects the time to permit the most. I believe that if rework in structural and fire, life, and safety disciplines is required early, more rework will be required by all of the engineering disciplines because those two systems of the facility affect the layout of mechanical, electrical, and plumbing.

**Question 3.** How can an adaptive algorithm be implemented into the simulation to allow continuous updating of model inputs? The current model distinguishes the category of projects by dollar amounts, mirroring how the FDD categorizes their projects. This categorization keeps the developed model consistent with the current organizational record keeping. It is also a way to relate the information when presenting the simulation model to the organization. However, because the model is set to use dollars, the model can become outdated in a few years because of inflation. Future work would consist of implementing an algorithm that can adjust for these changes to keep the model up to date and relevant. This algorithm would use the organization's existing data to change the categories in which the review, rework, and re-review characteristics are held.

**Question 4.** What is the system impact of using a dedicated review team on the time to permit? My initial assessment of the use of a dedicated review team is positive. However, further exploration would include dedicated review teams for smaller projects, i.e., projects in categories I and II. Category I and II projects represent the largest number of projects encountered by each OSHPD plan review region. It would be interesting to see how the system dynamics would be altered if a team were dedicated to solely review them. The FDD is looking at implementing a hybrid model of this dedicated review team by setting up times to review these small projects knowing that they require less rework, and permits can be issued with only slight changes to the drawings.

**Question 5.** What is the impact on the time to permit if rework is reduced in all drawing categories? I realize that the permitting of healthcare facilities in California is a system, therefore, I would expect that the reduction of rework percentages and review times of the other three project categories would substantially improve the time to permit for the entire system. The first way to improve the time to permit is to reduce the occurrences of rework in the system. Implementing a built-in quality process that avoids and removes errors in documents is the best way to improve the permitting process. The next step is to categorize and explore the documents required in submitting permitting plans and then detail the information each plan requires. OSHPD has tried to eliminate some of the rework by developing code application notices (CANs) and policy information notices (PINs) to reduce the amount of errors in submittals. For example, CAN 2-3403A provides design teams an acceptable approach to seismically retrofit single story hospital buildings (OSHPD 2008). However, by reviewing existing data, this procedure has not helped because the rework rates in structural review are still over 85%.

The FDD may benefit by developing a training program for design practitioners and investing money into a mobile training or webinar series that explains what information is required prior to plan submission. While the organization does charge a fee for reviewing documents, a disincentive program could be established charging extra fees when rework of permit documents is required. The fee would have to be high enough to ensure design teams delay the submittal of documents until they are more complete and accurate. The fee system could work with the first rework cycle being free, but imposing hefty fines during any subsequent rework cycles. Implementing a simulation model to test these management strategies would give insight into the overall impact to the system.

**Question 6.** What are the cost impacts of the causes of rework? This work does not attempt to track the cost implication of rework. Documenting the cost to rework items due to agency review will provide insight to the industry that real process improvement is required. It would be interesting to track the actual cost of reviews to what is charged by FDD, and relate that to how many rework cycles occur. It would also be interesting to look at the cost implication of implementing an alternative review process. Realizing the upfront design review work requires spending money, is the payback really worth the investment in regards to dollars? What is the impact of fewer rework cycles on the design and construction of the project? Ultimately, does having better permit drawings improve the construction of the healthcare facility project? Are there fewer change orders to the drawings and fewer requests for information from the contractor because the contractors were involved in the design process? What is the impact of an alternative review process on the field staff that reviews the construction process? Does the field staff provide fewer notices to the contractor? Does this improve delivery of healthcare facilities? In many of these questions, in Toyota's experience, the answer is "yes."

**Question 7.** What is the impact of the timing of changes on the flow of work for a mechanical contractor? Case study I used only generic resources (duct work is indistinguishable from piping). It would be interesting to explore the different types of rework that are encountered by the mechanical subcontractor. It would be interesting to compare the two types of work (dryside vs. wetside) that the company encounters. Is there more rework in ductwork or piping? This research would be case based because the setting of the project is important. Knowing what types of contracts and delivery model are being used affects project behavior.

In conclusion, the research presented in this dissertation answers a few questions on the effect of rework on the design and permitting of healthcare facilities, yet, raises many more questions that can be explored in the future. Furthermore, this research shows that process improvements can not be made individually, but requires a consolidated and collaborative effort by the entire industry. I know that this type of process improvement is daunting, but I am confident, through the case studies I present in this research, that process improvement can improve. This improvement will not only provide better healthcare for all, but people will want and strive to be a part of the design and construction industry.

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# Appendix A Causes of Rework Data

| **Description** | **First level** | **Second level** | **Third level** |
|---|---|---|---|
| Engineer drawings not used for construction | Construction Planning and Scheduling | Constructability problems | Drawings vs. field construction issues |
| Changes "ripple" through disciplines | Design Planning and Scheduling | Design changes | Scope changes |
| Drawings not correct or complete. | Design Planning and Scheduling | Errors and omissions | Inaccurate/ incorrect drawings |
| Equipment selection not properly timed | Design Planning and Scheduling | Improper equipment selection | Inappropriate timing for equipment selection |
| Customization / innovation | Design Planning and Scheduling | Inappropriate design process | Unable to handle customization/inno vation |
| Target costing batches too large | Design Planning and Scheduling | Inappropriate batch size | Large batch |
| Batch size | Design Planning and Scheduling | Inappropriate batch size | Large batch |
| Timing (continuous flow of work) | Design Planning and Scheduling | Inappropriate batch size | No continuous flow of work |
| Lack of appropriate resources (people, who draws what, design assist) | Design Planning and Scheduling | Inappropriate design process | Constrained resources |
| Not enough time - unrealistic promises, unexpected issues, failure of one part to deliver, other demands, fear | Design Planning and Scheduling | Inappropriate design process | Constrained resources |
| Lack of design team resources and everyone else's resources, too; lack of skills | Design Planning and Scheduling | Inappropriate design process | Constrained resources |
| Lack of work in 3D. | Design Planning and Scheduling | Inappropriate design process | Constrained resources |
| Slowest discipline determing critical path. | Design Planning and Scheduling | Inappropriate design process | Design held up by slowest discipline |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Design team reviews and decisions made in silos (no "big room"). | Design Planning and Scheduling | Inappropriate design process | Designing in isolation |
| No dimension lines | Design Planning and Scheduling | Inappropriate design process | errors & omissions |
| Incomplete unnecessary set to OSHPD | Design Planning and Scheduling | Inappropriate design process | errors & omissions |
| User group process - programming, schematic design (SD), design development (DD), Contract Documents (CD), Permitting, Construction Administration (CA) - Mistakes or delays in DD cause no delay in DD but delay the project 20 days in CD and 40 days in CA | Design Planning and Scheduling | Inappropriate design process | errors & omissions |
| Overprocessing - focus on wrong elements | Design Planning and Scheduling | Inappropriate design process | Focus on wrong elements |
| Use wrong person for task | Design Planning and Scheduling | Inappropriate design process | Improper skill assignment |
| Contractor specific plans and specifications | Design Planning and Scheduling | Inappropriate design process | Inadequte information |
| Incomplete design | Design Planning and Scheduling | Inappropriate design process | Incomplete design |
| Information needed by team members is not defined. | Design Planning and Scheduling | Inappropriate design process | Incomplete information |
| Focus on details too soon. | Design Planning and Scheduling | Inappropriate design process | Incomplete information |
| Using wrong processes for wrong client. | Design Planning and Scheduling | Inappropriate design process | Incorrect alignment of process |
| Design for multiple vendors/clients | Design Planning and Scheduling | Inappropriate design process | Incorrect information |
| [3] A/E selection process – lost time/revenue if not selected | Design Planning and Scheduling | Inappropriate design process | Inefficient decision making |

| Description | First level | Second level | Third level |
| --- | --- | --- | --- |
| [2] Infrastructure sizing/locations (wastes # 1, 6, 7, 8) too early | Design Planning and Scheduling | Inappropriate design process | Inefficient decision making |
| [1] Timing of selection of CM/GC | Design Planning and Scheduling | Inappropriate design process | Inefficient decision making |
| Early or late engagement of key A/E/CMSC/party | Design Planning and Scheduling | Inappropriate design process | Inefficient decision making |
| User group/input process | Design Planning and Scheduling | Inappropriate design process | Inefficient decision making |
| Lack of alignment between system and affiliate | Design Planning and Scheduling | Inappropriate design process | Inefficient decision making |
| Information loss at hand off (technology) | Design Planning and Scheduling | Inappropriate design process | Information lost at handoff |
| Design - constructability disconnect | Design Planning and Scheduling | Inappropriate design process | Information not aligned |
| [1] Unclear expectations of ‘when’ | Design Planning and Scheduling | Inappropriate design process | Lack of complete information |
| [2] Prelim MEP coordination drawings | Design Planning and Scheduling | Inappropriate design process | Lack of complete information |
| [1] Clearly define OSHPD submittal package | Design Planning and Scheduling | Inappropriate design process | Lack of complete information |
| Design disciplines not hearing user group concerns first hand, or not having early "vision" discussions with client | Design Planning and Scheduling | Inappropriate design process | Lack of complete information |
| Shift of design intent from SD's | Design Planning and Scheduling | Inappropriate design process | Lack of complete information |
| Deferred approvals | Design Planning and Scheduling | Inappropriate design process | Lack of complete information |
| Lack of coordination between design team | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| Lack of coordination (technical disciplines) | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| Communication (RFI's) | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Shop drawing process occurs late and without collaboration and is redrawn | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| RFI process | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| Poor information transfer - not understandingwhat others need, not understanding possible prevision, not easy to understand, too late | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| Poor information - accuracy / preliminaries, - incompleteness, - timing, - changes not marked | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| Out of synch. processes. | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| Expectation about who provides information | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| [1] user group meetings – unclear process | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| [2] third-party MEP review/coordination | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| Submittals process (including post-approvals) | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| [1] End of phase submittal package (batch sizes) & transition between phases | Design Planning and Scheduling | Inappropriate design process | Lack of coordination |
| Lack of standardization (studs, stairs) optimizing the pieces (steel tonnage) | Design Planning and Scheduling | Inappropriate design process | Lack of standardized design elements |
| BC turnaround | Design Planning and Scheduling | Inappropriate design process | Length of time for backcheck completion |
| Out of synch. with owner values | Design Planning and Scheduling | Inappropriate design process | Not understanding owner values |

| Description | First level | Second level | Third level |
| --- | --- | --- | --- |
| Designer/fabricator not aligned | Design Planning and Scheduling | Inappropriate design process | Outcomes not aligned |
| studies, number of meetings, unclear process, don’t have right people in the room | Design Planning and Scheduling | Inappropriate design process | Overprocessing |
| [2] Design team detail drawings vs. shop drawings | Design Planning and Scheduling | Inappropriate design process | Overprocessing |
| Developing a design just for critique or contract conformance (especially MEP) | Design Planning and Scheduling | Inappropriate design process | Overprocessing |
| Unnecessary detailing. | Design Planning and Scheduling | Inappropriate design process | Overproduction |
| Information put in too many places | Design Planning and Scheduling | Inappropriate design process | Overproduction |
| Exploring design options outside of project scope or budget | Design Planning and Scheduling | Inappropriate design process | Overproduction |
| Moving forward without approvals | Design Planning and Scheduling | Inappropriate design process | Review process |
| Something in the spec you don't understand (see staffing) | Design Planning and Scheduling | Inappropriate design process | Unclear codes |
| [1+] Unclear definition of the deliverables | Design Planning and Scheduling | Inappropriate review process | Lack of complete information |
| Lack of project introduction to OSHPD. | Design Planning and Scheduling | Inappropriate review process | Lack of project information |
| Waiting for determination of occupancy judgment (“1”/”B”) | Design Planning and Scheduling | Inappropriate review process | Length of time for review |
| [3] Code compliance drawings not needed for construction | Design Planning and Scheduling | Inappropriate review process | Overprocessing |
| Questions instead of comments (<u>document</u> / code <u>clarity</u>) | Design Planning and Scheduling | Inappropriate review process | Unclear comments by plan reviewers |

| Description | First level | Second level | Third level |
|---|---|---|---|
| "BIN" time - waiting to review. | Design Planning and Scheduling | Inappropriate review process | Wait time for drawing review |
| Drawings submitted too soon. | Design Planning and Scheduling | Poor Document Control | Improper drawing delivery |
| Accuracy and correctness of labels (alignment with customer). | Design Planning and Scheduling | Poor Document Control | Inaccurate/ incorrect labels |
| Document organization and format | Design Planning and Scheduling | Poor Document Control | Inadequate document organization |
| Inconsistent document organization communication | Design Planning and Scheduling | Poor Document Control | Inconsistent document organization |
| Underproduction - not the right documents or information | Design Planning and Scheduling | Poor Document Control | Incorrect package content |
| Document organization | Design Planning and Scheduling | Poor Document Control | Incorrect package content |
| Unnecessary drawings packaged in overall set or to each "client" | Design Planning and Scheduling | Poor Document Control | Incorrect package content |
| Supplemental documents | Design Planning and Scheduling | Poor Document Control | Incorrect package content |
| Overproduction - unnecessary documents (repetition of details) | Design Planning and Scheduling | Poor Document Control | Overproduction |
| Failure to identify AMOC's | Design Planning and Scheduling | Scope changes | Bad process assumptions (C3) |
| [1] Changes during CD phase | Design Planning and Scheduling | Scope changes | Late owner input (A13) |
| Standards Change (example:  DHOT) - Programming | Design Review | Code Changes | Impact of code changes on design |
| Standards Change (example:  DHOT) - SD | Design Review | Code Changes | Impact of code changes on design |
| Standards Change (example:  DHOT) - DD | Design Review | Code Changes | Impact of code changes on design |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Standards Change (example: DHOT) - CD | Design Review | Code Changes | Impact of code changes on design |
| Standards Change (example: DHOT) - Permit | Design Review | Code Changes | Impact of code changes on design |
| Standards Change (example: DHOT) - CA | Design Review | Code Changes | Impact of code changes on design |
| [1] Timing of input from OSHPD | Design Review | Inappropriate review process | Improper timing of input |
| Misalignment of code interpretations between design team and OSHPD - program flex concepts not communicated and vetted) | Design Review | Inappropriate review process | Inadequate information |
| Incomplete OSHPD reviews -> later comments | Design Review | Inappropriate review process | Incomplete information |
| Length of approval process | Design Review | Inappropriate review process | Inefficient review process |
| OSHPD approval loop | Design Review | Inappropriate review process | Inefficient review process |
| Inappropriate review (coordinating) | Design Review | Inappropriate review process | Lack of coordination |
| Lack of documentation and agreements on interpretation | Design Review | Inappropriate review process | Lack of coordination |
| Code interpretation during DD's | Design Review | Inappropriate review process | Lack of standardized review |
| Reviewer preference of solution (multiple reviewers) | Design Review | Inappropriate review process | Lack of standardized review |
| Variations in code interpretations | Design Review | Inappropriate review process | Lack of standardized review |
| Lack of consistency in review staff (technical and experience) | Design Review | Inappropriate review process | Lack of standardized review |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Interpretation of code by field staff | Design Review | Inappropriate review process | Lack of standardized review |
| OSHPD looking at trivials | Design Review | Inappropriate review process | Lack of standardized review |
| [3] outside peer review | Design Review | Inappropriate review process | Lack of standardized review |
| OSHPD cycle time / que time, in series | Design Review | Inappropriate review process | Length of review |
| [1] OSHPD backcheck process | Design Review | Inappropriate review process | Length of review |
| Gaps between reviews (loss of knowledge or familiarity) | Design Review | Inappropriate review process | Project review unfamiliarity |
| Different understandings of what OSHPD must have | Design Review | Inappropriate review process | Unclear definition of needs |
| Plan checker learning curve | Design Review | Inappropriate review process | Untrained personnel |
| Inconsistence of reviewers | Design Review | Inappropriate review process | Untrained personnel |
| Lack of project champion | Leadership and Communication | Ineffective management of project team | Lack of a sense of ownership within the team |
| Lack of vision/guidingprojects (determining value). | Leadership and Communication | Ineffective management of project team | Lack of a sense of ownership within the team |
| Failure to communicate project goals or assumptions to team. | Leadership and Communication | Ineffective management of project team | Poor role definition of key players for authority & responsibility |
| Equipment changes (exmpl.: imaging/big, 64 slice) - programming | Material & Equipment Supply | Equipment changes | Change in equipment item/requirements/ business case |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Equipment changes (example: imaging/big, 64 slice) - SD | Material & Equipment Supply | Equipment changes | Change in equipment item/requirements/ business case |
| Equipment changes (example: imaging/big, 64 slice) - DD | Material & Equipment Supply | Equipment changes | Change in equipment item/requirements/ business case |
| Equipment changes (example: imaging/big, 64 slice) - CD | Material & Equipment Supply | Equipment changes | Change in equipment item/requirements/ business case |
| Equipment changes (example: imaging/big, 64 slice) - Permitting - we won't do it | Material & Equipment Supply | Equipment changes | Change in equipment item/requirements/ business case |
| Equipment changes (example: imaging/big, 64 slice) - CA (60 person days contractor, 45 person days designer) | Material & Equipment Supply | Equipment changes | Change in equipment item/requirements/ business case |
| Addtnl Bus. Case Change (exmpl: birthing=> cardiac) - Prog | Planning, programming and budgeting | Change in business case | Lack of commitment to business case |
| Addtnl Bus. Case Change (exmpl: birthing=> cardiac) - SD | Planning, programming and budgeting | Change in business case | Lack of commitment to business case |
| Addtnl Bus. Case Change (exmpl: birthing=> cardiac) - DD | Planning, programming and budgeting | Change in business case | Lack of commitment to business case |
| Addtnl Bus. Case Change (exmpl: birthing=> cardiac) - CD | Planning, programming and budgeting | Change in business case | Lack of commitment to business case |
| Addtnl Bus. Case Change (exmpl: birthing=> cardiac) - Perm. | Planning, programming and budgeting | Change in business case | Lack of commitment to business case |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Addtnl Bus. Case Change (exmpl: birthing=> cardiac) - CA | Planning, programming and budgeting | Change in business case | Lack of commitment to business case |
| User Group Change (example: Pharmacy) - Programming | Planning, programming and budgeting | Change in user groups | Lack of information handoff between personnel changes |
| User Group Change (example: Pharmacy) - SD | Planning, programming and budgeting | Change in user groups | Lack of information handoff between personnel changes |
| User Group Change (example: Pharmacy) - DD | Planning, programming and budgeting | Change in user groups | Lack of information handoff between personnel changes |
| User Group Change (example: Pharmacy) - CD | Planning, programming and budgeting | Change in user groups | Lack of information handoff between personnel changes |
| User Group Change (example: Pharmacy) - Permit (30 days time lost here goes to 40 days resoure person days extra in CA) | Planning, programming and budgeting | Change in user groups | Lack of information handoff between personnel changes |
| User Group Change (example: Pharmacy) - CA | Planning, programming and budgeting | Change in user groups | Lack of information handoff between personnel changes |
| Escalation - programming | Planning, programming and budgeting | Escalation costs | Escalation costs |
| Escalation - SD ($3 million per month) | Planning, programming and budgeting | Escalation costs | Escalation costs |
| Escalation - DD ($3 million per month) | Planning, programming and budgeting | Escalation costs | Escalation costs |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Escalation - CD ($3 million per month) | Planning, programming and budgeting | Escalation costs | Escalation costs |
| Escalation - Permitting ($3 million per month - $9 million total) | Planning, programming and budgeting | Escalation costs | Escalation costs |
| Escalation - CA | Planning, programming and budgeting | Escalation costs | Escalation costs |
| Conflicts between owner | Planning, programming and budgeting | Lack of owner commitment | Not understanding owner differences |
| Starting SD's without business plan approval (problem solutionpriorto problem definition) | Planning, programming and budgeting | Lack of owner commitment | Failure to approve business plan |
| Incomplete SD's / program still unresolved | Planning, programming and budgeting | Lack of owner commitment | Failure to approve business plan |
| Lack of project definition | Planning, programming and budgeting | Lack of owner commitment | Inadequate project definition |
| Budget not defined. | Planning, programming and budgeting | Lack of owner commitment | Inadequate project planning |
| Client decisions - right person/stick to it | Planning, programming and budgeting | Lack of owner commitment | Inefficient decision making |
| [1] leadership/user approval process | Planning, programming and budgeting | Lack of owner commitment | Inefficient decision making |
| [1] budget validation/VE & constructability | Planning, programming and budgeting | Lack of owner commitment | Inefficient decision making |
| [2] Business lacking description of what is ‘value’ | Planning, programming and budgeting | Lack of owner commitment | Inefficient decision making |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Lack of commitment to scope (living with your decision) | Planning, programming and budgeting | Lack of owner commitment | Inefficient decision making |
| [1] budget go/no go | Planning, programming and budgeting | Lack of owner commitment | Lack of commitment to business case |
| Timing - over the fence budget and constructability | Planning, programming and budgeting | Lack of owner commitment | Lack of commitment to business case |
| User group behavior | Planning, programming and budgeting | Lack of owner commitment | Lack of coordination |
| Disconnect money from design too long | Planning, programming and budgeting | Lack of owner commitment | Lack of detailed project budget |
| Waiting for owner deicsions / approvals | Planning, programming and budgeting | Lack of owner commitment | Lack of owner decision |
| Changes in "client" or team | Planning, programming and budgeting | Lack of owner commitment | Leadership personnel changes |
| Lack of flexibililty of program to accommodate outside factors (estimation, demand for service) | Planning, programming and budgeting | Lack of owner flexibility | Inadequte project planning |
| Lack of understanding of business process by endusers (standardization) | Planning, programming and budgeting | Lack of owner knowledge | Incomplete information |
| Owner Changes - Programming | Planning, programming and budgeting | Owner changes | Owner changes |
| Owner Changes - SD | Planning, programming and budgeting | Owner changes | Owner changes |
| Owner Changes - DD | Planning, programming and budgeting | Owner changes | Owner changes |

| Description | First level | Second level | Third level |
|---|---|---|---|
| Owner Changes - CD (per time - 0 time inc. per 30 Days) | Planning, programming and budgeting | Owner changes | Owner changes |
| Owner Changes - Permitting | Planning, programming and budgeting | Owner changes | Owner changes |
| Owner Changes - CA (50 PD UES, 60 PD contractor) | Planning, programming and budgeting | Owner changes | Owner changes |

# Appendix B STROBOSCOPE Code for Demand and Capacity Simulations

```
/*************************************************************************************************
/* Stroboscope source file generated from Visio drawing C:\Documents and Settings\Peter
Feng\Desktop\Berkeley Working Folder\PhD Research\4. Case Studies\2. OSHPD\1. OSHPD
Simulation (9 Jul 08).vsd
/*************************************************************************************************
VARIABLE Type1proj                  1000;

VARIABLE NoArchRev                  5;

MVAVGCOLLECTOR PermitTime           1;

MVAVGCOLLECTOR AvePermitTime        10;
/*************************************************************************************************
/* Definition of resource types

/ Define the drawing sets as a resource. This will be the primary resource that flows through the
/ model. With each drawing set resource a number of characteristics will be assigned. These
/ characteristics will track how many times a drawing is reviewed and will serve as a counter.
/ Multiple subtypes of drawing set will be defined. Three different sizes will be established
/ to represent the actual types of drawings. Small, medium and large projects will be defined
/ Each of the sizes of drawings can represent either new construction or renovation.

CHARTYPE    DrawingSet                        Size    ArchMu  r; /DR
/=======================================================================
SUBTYPE             DrawingSet        Type1          1               1        80;
/--------------------------------------------------

SAVEPROPS   DrawingSet ArchR RevError;
SAVEPROPS   DrawingSet RandomNo TotNoRev EntryNumber;
SAVEPROPS   DrawingSet Reworked;
SAVEPROPS   DrawingSet ReworkPercent ReworkFactor;
SAVEPROPS   DrawingSet ArchTime CompleteTime AveTime;
SAVEPROPS   DrawingSet ProjNo;

VARPROP     DrawingSet DiscipProp RandomNo;
VARPROP     DrawingSet DiscipProp1        ProjNo;

GENTYPE     ArchPerson; /AP
GENTYPE     FlowPerson; /FP

/*************************************************************************************************
/* General section for problem parameters
/*************************************************************************************************
/* Definition of network nodes

/ Creates a queue that will hold characterized resources

QUEUE               Projects DrawingSet;
```

```
/ Combi that initializes each drawings set so the characteristics are set to zero

COMBI                   Initialize;

/ Creates a queue that represents an area to hold drawings when waiting to be worked on by the
/ design review specialist

QUEUE                   DrawingTable DrawingSet;

/ Series of combi that represent the actual review conducted by the design specialist. The
process
/ times associated with each combi was taken from database provided by OSHPD

COMBI                   ArchRev;

/ Combi that reviews each drawings will only draw from the Drawing Table if each resource has
/ 1 for each of the review characteristics
COMBI                   Review;
NORMAL                  Review1;
NORMAL                  Review2;

/Combi for the rereview process, will be sent drawings from a random calculation of who is
assigned error
COMBI                   ReReviewA;

/ Creates a series of queues that hold the design review specialist resource. This resource is the
/ one of the limiting factors that can throttle the speed of the review. With more resources, more
/ drawings can be reviewed.

QUEUE                   ArchPer ArchPerson;

/ Create Queue for rework decision
QUEUE                   Complete DrawingSet;
QUEUE                   Rework DrawingSet;

/ Create queue for reporting information
QUEUE                   Complete1 DrawingSet;
COMBI                   Report;

/ Create queue to control inflow of projects
QUEUE                   Flow FlowPerson;
/**********************************************************************************************
/* Definition of forks

FORK                    ReworkDecision DrawingSet;
/**********************************************************************************************
/* Definition of network Links


/ Created below are the links for the model system. The links with DS in the name represent the
flow
/ of drawing set resources.
/ The links with AP, SP, MP, EP and FP represent the flow of design review personnel.

LINK                    DS1 Projects Initialize;
LINK                    DS2 Initialize DrawingTable;
```

```
LINK                    FL1 Flow Initialize;
LINK                    FL2 Initialize Flow;

LINK                    ArchDS DrawingTable ArchRev;
LINK                    ArchDSRet ArchRev DrawingTable;

LINK                    AP1 ArchPer ArchRev;
LINK                    APRet ArchRev ArchPer;

LINK                    RD1 DrawingTable Review;
LINK                    RD1A Review Review1 DrawingSet;

LINK                    RD2 Review1 ReworkDecision;
LINK                    RD3     ReworkDecision Complete;
LINK                    RD4 ReworkDecision Rework;
LINK                    RD5 Review1 Review2 DrawingSet;
LINK                    RD6 Review2 Complete;

/ Architect ReReview Links
LINK                    RDA     Rework ReReviewA;
LINK                    RDARet          ReReviewA Review1 DrawingSet;

LINK                    RRA     ArchPer ReReviewA;
LINK                    RRARet          ReReviewA ArchPer;

/ Links for reporting information
LINK                    R1              Complete Report;
LINK                    R2              Report Complete1;
/*********************************************************************************************
/* Definition of global variables and programing objects

FILTER ArchRevF DrawingSet ‘ArchR==0’;

FILTER ReworkF DrawingSet ‘ArchR==1’;

FILTER DrawingAtFront DrawingSet ‘RandomNo==DrawingTable.RandomNo.MinVal’;
FILTER DrawingAtFront1 DrawingSet ‘ProjNo==Complete.ProjNo.MinVal’;

FILTER ReworkedEnough DrawingSet ‘Reworked==3’;

DISCIPLINE DrawingTable DiscipProp;
DISCIPLINE Complete  DiscipProp1;
/*********************************************************************************************
/* Entry of resources into Projects

/ This step creates the number of drawing sets that will be loaded into the system. Three types of
/ projects will be loaded into the system to represent small, medium, or large projects either new
/ construction or renovated.

/INIT Projects Type1proj Type1;

/INIT ArchPer NoArchRev;
/INIT Flow 1;
/*********************************************************************************************
/* Startup of Initialize
```

```
ONDRAW DS1            ASSIGN ProjNo ResNum;

DURATION              Initialize '1';
/*********************************************************************************************
/* Termination of Initialize

/ This initializes the properties of each of the drawings that flow through the model. Each
ONRELEASE DS2 ASSIGN ArchR 0;

ONRELEASE DS2 ASSIGN ArchTime SimTime;

/ ONRELEASE DS2 PRINT StdOutput "Time\t%5.1f\t" SimTime;

/ ONRELEASE DS2 PRINT StdOutput "Queue\t%5.0f\t\n" DrawingTable.Type1.Count;
/*********************************************************************************************
/* Entry of resources into DrawingTable
/*********************************************************************************************
/* Statements to assist in the definition of attributes of ArchRev and its related links
/*********************************************************************************************
/* Startup of ArchRev

/ This criterion will only pull drawings where the ArchR is less than one. This step ensures that
/ the drawings will only be reviewed once by the architect before a rework decision is made.

/ This step will only pull a drawing set to review if there is one or more drawings in the queue

/ ENOUGH                      ArchDS 'DrawingTable.ArchRevF.Count>=1';

DRAWWHERE             ArchDS 'ArchR==0&DrawingAtFront';

/ ONDRAW ArchDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW ArchDS PRINT StdOutput "\tin ArchRev at\t%5.1f\n" SimTime;

/ ONDRAW ArchDS ASSIGN ArchTime SimTime;

/ This criterion requires one architect to be available to review the drawings set.

ENOUGH                        AP1 'ArchPer.CurCount>= 1';

/ This step lists the duration of the architectural review which will be a normal distribution.
/ This step will expand to incorporate three types of review, small, medium and large. The
/ durations will be taken from the database provided.

DURATION              ArchRev '1';
/*********************************************************************************************
/* Termination of ArchRev

/ This resets the value to one once the drawing has been reviewed by the architect.


ONRELEASE ArchDSRet ASSIGN ArchR ArchR+1;

/*********************************************************************************************
/* Startup of Review
```

```
ENOUGH RD1 ‘DrawingTable.ReworkF.Count>=1’;

DRAWWHERE RD1 ‘ArchR==1’;

ONDRAW RD1 ReworkFactor 1;

ONDRAW RD1 Reworked 0;

DURATION Review ‘0’;
/*****************************************************************************************************
/* Termination of Review
/*****************************************************************************************************
/* Startup of Review1

DURATION Review1 ‘0’;
/*****************************************************************************************************
/* Termination of Review1

/* Rework factor, set to 1 if drawingset has never been repaired and to 2 if it has

STRENGTH RD4 Review1.DrawingSet.r;

STRENGTH RD3 100-Review1.DrawingSet.r;
/*****************************************************************************************************
/* Startup of Review2

/ ONRELEASE RD5 ‘Review1.ReworkedEnough.Count>=1’;

/ DRAWWHERE RD5 ‘Reworked==3’;

DURATION Review1 ‘0’;
/*****************************************************************************************************
/* Termination of Review1
/*****************************************************************************************************
/* Startup of OwnerRework

ONFLOW RD3 ASSIGN CompleteTime SimTime;

/Turn on these print statements to show the rework factor.

/ ONRELEASE RD6 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONRELEASE RD6 PRINT StdOutput “\tRework Percent \t%5.1f\n” ‘r/ReworkFactor’;
/*****************************************************************************************************
/* Termination of OwnerRework

/ ONRELEASE RD6 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONRELEASE RD6 PRINT StdOutput “\tOwner Rework Time \t%5.1f\n” OwnerReworkTotal;
/*****************************************************************************************************
/* Startup of ReReviewA

PRIORITY ReReviewA ‘Rework.CurCount>0 ? 10 : 0’;

DURATION ReReviewA ‘1’;
```

```
/*****************************************************************************************************
/* Termination of ReReviewA

ONRELEASE RDARet ASSIGN Reworked Reworked+1;

ONRELEASE RDARet ASSIGN ReworkFactor ReworkFactor+1;
/*****************************************************************************************************
/* Startup of Report

ENOUGH R1 ‘Complete.ReworkF.Count==Type1proj’;

/ ENOUGH R1 ‘Complete.ReworkF.Count==10’;

DRAWWHERE R1 ‘DrawingAtFront1’;

DRAWUNTIL R1 ‘Report.DrawingSet.Count==Type1proj’ ;

DURATION Report 0;

ONRELEASE R2 COLLECT PermitTime CompleteTime-ArchTime;

ONRELEASE R2 COLLECT AvePermitTime CompleteTime-ArchTime;

                    ONRELEASE R2 PRINT StdOutput “Proj No.\t%4.0f\t” ResNum;


                    ONRELEASE R2 PRINT StdOutput “Average Time\t%5.1f\t\n”
AvePermitTime.AveVal;

ONRELEASE R2 ASSIGN AveTime AvePermitTime.AveVal;
/*****************************************************************************************************
/* Termination of Report
/*****************************************************************************************************
/ Introduce the TimeStep combi so we will be certain that the simulation clock reaches the exact
/ times at which we want to collect data

VARIABLE TimeStepSize 10;
COMBI TimeStep;

SEMAPHORE TimeStep !TimeStep.CurInst;

/ Allow only one instance to exist at a time.

DURATION TimeStep TimeStepSize;

/ Data will be collected every X=TimeStepSize days.

/ BEFOREEND TimeStep PRINT StdOutput “Time is now %6.4f \n” SimTime;

/ Make sure the simulation does not go on forever (TimeStep would). Set simulation end time at
/ 1200 which should be upper bound on the project completion time.

VARIABLE EndTime 1200;

SIMULATEUNTIL SimTime>=EndTime;
/*****************************************************************************************************
```

```
/*      COLLECTORS
/*************************************************************************************************
/ Define collectors that will gather data over multiple simulation runs.
/ Collectors need to be persistent (add '*' to their name to make them persistent) or else the data
/ will get lost when the CLEAR command is invoked upon start of a new iteration.

COLLECTOR ProjDuration*;
COLLECTOR InstallFirstCollector*;

SAVEVALUE CurrentStep 0;

WHILE CurrentStep<=EndTime;

        COLLECTOR QueueSize$<CurrentStep>$*;
        COLLECTOR LeadTime$<CurrentStep>$*;

        ASSIGN CurrentStep CurrentStep+TimeStepSize;
WEND;
/*************************************************************************************************
/* ITERATION
/*************************************************************************************************
VARIABLE NrIterations 30;
SAVEVALUE CurrentIteration* 1;
SAVEVALUE CurrentStepTwo* 0;

WHILE CurrentIteration<=NrIterations;
        CLEAR;
/*************************************************************************************************
/* Entry of resources into Projects

/ This step creates the number of drawing sets that will be loaded into the system. Three types of
/ projects will be loaded into the system to represent small, medium, or large projects either new
/ construction or renovated.

INIT Projects Type1proj Type1;
INIT ArchPer NoArchRev;
INIT Flow 1;

WHILE CurrentStepTwo<=EndTime;

        SIMULATEUNTIL SimTime>=CurrentStepTwo;

        COLLECT QueueSize$<CurrentStepTwo>$ DrawingTable.Type1.Count;

        ASSIGN CurrentStepTwo CurrentStepTwo+TimeStepSize;

WEND;

        ASSIGN CurrentIteration CurrentIteration+1;

        ASSIGN CurrentStepTwo 0;
        PRINT StdOutput "\n\n";

WEND;
```

# Appendix C STROBOSCOPE Code for Effect of Alternative Review on Workflow

## Model 1

```
/*************************************************************************************************
/* Stroboscope source file generated from Visio drawing C:\Documents and Settings\Peter
Feng\Desktop\Berkeley Working Folder\PhD Research\4. Case Studies\2. OSHPD\1. OSHPD
Simulation (9 Jul 08).vsd
/*************************************************************************************************
VARIABLE Type1proj                50;
VARIABLE Type2proj                100;
VARIABLE Type3proj                35;
VARIABLE Type4proj                20;
VARIABLE Type5proj                0;

VARIABLE NoArchRev                1;
VARIABLE NoStrucRev               1;
VARIABLE NoMechRev                1;
VARIABLE NoElecRev                1;
VARIABLE NoFLSRev                 1;

VARIABLE RevAssignError           'Rnd[]          <= 1/5 ? 100:
                                                   LastRnd[]      <= 2/5 ? 200:
                                                   LastRnd[]      <= 3/5 ? 300:
                                                   LastRnd[]      <= 4/5 ? 400: 500';

VARIABLE RandomNumber             'Rnd[]';

MVAVGCOLLECTOR PermitTime 5;
/*************************************************************************************************
/* Definition of resource types

/ Define the drawing sets as a resource. This will be the primary resource that flows through the
/ model. With each drawing set resource a number of characteristics will be assigned. These
/ characteristics will track how many times a drawing is reviewed and will serve as a counter.
/ Multiple subtypes of drawing set will be defined. Three different sizes will be established
/ to represent the actual types of drawings. Small, medium and large projects will be defined
/ Each of the sizes of drawings can represent either new construction or renovation.

CHARTYPE     DrawingSet     Size     ArchMu          ArchSD          StructMu
         StructSD          MechMu             MechSD          ElectMu         ElectSD         FLSMu
         FLSSD             r                  ORewMu          ORewSD          RRevAMu
         RRevASD            RRevSMu           RRevSSD         RRevMMu         RRevMSD
         RRevEMu           RRevESD            RRevFMu         RRevFSD         ; /DR
/=============================================================================
SUBTYPE DrawingSet  Type1   1     1.17            0.17            1.85
         0.4               1.07               0.05            1.07            0.05            1.36
         0.21              82       5                 1                 1.44
         0.42              1.17               0.09            1.39            0.25
         1.03              0.03               1.34            0.19            ;
/-------------------------------------------------
```

```
SUBTYPE DrawingSet  Type2   10      1.66            0.26            2.59
            0.4             3.79            1.17            0.07            1.38            0.22
            93              10              2               1.68            0.26
            2.3             0.49            1.17            0.2             1.07
            0.04            1.96            0.32                            ;
/--------------------------------------------------
SUBTYPE DrawingSet  Type3   100     2.85            0.7             8.32
            1.1             4.37            0.8             4.39            1.26            4.0
            0.76            99              20              3               1.6
            0.29            6.04            0.92            1.82            0.45
            1.44            0.2             4.19            1.17            ;
/--------------------------------------------------
SUBTYPE DrawingSet  Type4   100     8.38            1.82            21.5
            6.25            10.9            2.38            8.27            1.94            18.2
            3.43            88              70              5               4.05
            1.53            10.8            2.9             4.8             1.51
            2.7             0.72            7.57            1.8             ;
/--------------------------------------------------
SUBTYPE DrawingSet  Type5   100     8.38            1.82            21.5
            6.25            10.9            2.38            8.27            1.94            18.2
            3.43            88              70              5               4.05
            1.53            10.8            2.9             4.8             1.51
            2.7             0.72            7.57            1.8             ;
/--------------------------------------------------

SAVEPROPS   DrawingSet ArchR StructR MechR ElectR FLSR RevError;
SAVEPROPS   DrawingSet RandomNo TotNoRev EntryNumber;
SAVEPROPS   DrawingSet Reworked;
SAVEPROPS   DrawingSet ReworkPercent ReworkFactor;
SAVEPROPS   DrawingSet ArchTime StructTime MechTime ElectTime FLSTime CompleteTime;
SAVEPROPS   DrawingSet OwnerStart OwnerEnd OwnerReworkTotal;
SAVEPROPS   DrawingSet ProjNo;

VARPROP DrawingSet DiscipProp RandomNo;
VARPROP DrawingSet DiscipProp1 ProjNo;

CHARTYPE    ReviewPer                                   Type; /RP
/==========================================================================
SUBTYPE             ReviewPer           Arch            100;
SUBTYPE             ReviewPer           Struct          200;
SUBTYPE             ReviewPer           Mech            300;
SUBTYPE             ReviewPer           Elect           400;
SUBTYPE             ReviewPer           FLS                     500;
/--------------------------------------------------

/ Define five resources that represent the design review personnel.

GENTYPE             OArchPerson; /AP
/*****************************************************************************************
/* General section for problem parameters
/*****************************************************************************************
/* Definition of network nodes

/ Creates a queue that will hold characterized resources

QUEUE               Projects DrawingSet;
```

```
/ Combi that initializes each drawings set so the characteristics are set to zero

COMBI                   Initialize;

/ Creates a queue that represents an area to hold drawings when waiting to be worked on by the
/ design review specialist

QUEUE                   DrawingTable DrawingSet;

/ Series of combi that represent the actual review conducted by the design specialist. The
process
/ times associated with each combi was taken from database provided by OSHPD

COMBI                   ArchRev;

COMBI                   StructRev;
COMBI                   MechRev;
COMBI                   ElectRev;
COMBI                   FLSRev;

/ Combi that reviews each drawings will only draw from the Drawing Table if each resource has
/ 1 for each of the review characteristics
COMBI                   Review;
NORMAL                          Review1;
COMBI                   OwnerRework;

/Combi for the rereview process, will be sent drawings from a random calculation of who is
assigned error
COMBI                   ReReviewA;
COMBI                   ReReviewS;
COMBI                   ReReviewM;
COMBI                   ReReviewE;
COMBI                   ReReviewF;

/ Creates a series of queues that hold the design review specialist resource. This resource is the
/ one of the limiting factors that can throttle the speed of the review. With more resources, more
/ drawings can be reviewed.


QUEUE                   ArchPer ReviewPer;
QUEUE                   StructPer ReviewPer;
QUEUE                   MechPer ReviewPer;
QUEUE                   ElectPer ReviewPer;
QUEUE                   FLSPer ReviewPer;

QUEUE                   OArchPer OArchPerson;

/ Create Queue for rework decision
QUEUE                   Complete DrawingSet;
QUEUE                   Rework DrawingSet;
QUEUE                   Resubmit DrawingSet;

/ Create queues for characterized resources, reviewers for each discipline
QUEUE                   ReworkRevA ReviewPer;
QUEUE                   ReworkRevS ReviewPer;
```

```
QUEUE                 ReworkRevM ReviewPer;
QUEUE                 ReworkRevE ReviewPer;
QUEUE                 ReworkRevF ReviewPer;

/ Create queue for reporting information
QUEUE                         Complete1 DrawingSet;
COMBI                 Report;
/*************************************************************************************************
/* Definition of forks
FORK                  ReworkDecision DrawingSet;
/*************************************************************************************************
/* Definition of network Links

/ Created below are the links for the model system. The links with DS in the name represent the
flow
/ of drawing set resources.
/ The links with AP, SP, MP, EP and FP represent the flow of design review personnel.

LINK                  DS1 Projects Initialize;

LINK                  DS2 Initialize DrawingTable;

LINK                  ArchDS DrawingTable ArchRev;

LINK                  ArchDSRet ArchRev DrawingTable;

LINK                  StructDS DrawingTable StructRev;

LINK                  StructDSRet StructRev DrawingTable;
LINK                  MechDS DrawingTable MechRev;
LINK                  MechDSRet MechRev DrawingTable;
LINK                  ElectDS DrawingTable ElectRev;
LINK                  ElectDSRet ElectRev DrawingTable;
LINK                  FLSDS DrawingTable FLSRev;
LINK                  FLSDSRet FLSRev DrawingTable;

LINK                  AP1 ArchPer ArchRev;

LINK                  APRet ArchRev ArchPer;

LINK                  SP1 StructPer StructRev;

LINK                  SPRet StructRev StructPer;
LINK                  MP1 MechPer MechRev;
LINK                  MPRet MechRev MechPer;
LINK                  EP1 ElectPer ElectRev;
LINK                  EPRet ElectRev ElectPer;
LINK                  FP1 FLSPer FLSRev;
LINK                  FPRet FLSRev FLSPer;

LINK                  RD1 DrawingTable Review;

LINK                  RD1A Review Review1 DrawingSet;

LINK                  RD2 Review1 ReworkDecision;
LINK                  RD3     ReworkDecision Complete;
```

```
LINK                    RD4 ReworkDecision Rework;
LINK                    RD5 Rework OwnerRework;
LINK                    RD6 OwnerRework Resubmit;

LINK                    OR1 OArchPer OwnerRework;
LINK                    OR2 OwnerRework OArchPer;

/ Architect ReReview Links
LINK                    RDA     Resubmit ReReviewA;
LINK                    RDARet          ReReviewA Review1 DrawingSet;

LINK                    RRA     ReworkRevA ReReviewA;
LINK                    RRARet          ReReviewA ReworkRevA;

/ Structural ReReview Links
LINK                    RDS     Resubmit ReReviewS;
LINK                    RDSRet          ReReviewS Review1 DrawingSet;

LINK                    RRS             ReworkRevS ReReviewS;
LINK                    RRSRet          ReReviewS ReworkRevS;

/ Mechanical ReReview Links
LINK                    RDM     Resubmit ReReviewM;
LINK                    RDMRet          ReReviewM Review1 DrawingSet;

LINK                    RRM             ReworkRevM ReReviewM;
LINK                    RRMRet          ReReviewM ReworkRevM;

/ Electrical ReReview Links
LINK                    RDE     Resubmit ReReviewE;
LINK                    RDERet          ReReviewE Review1 DrawingSet;

LINK                    RRE             ReworkRevE ReReviewE;
LINK                    RRERet          ReReviewE ReworkRevE;

/ FLS ReReview Links
LINK                    RDF     Resubmit ReReviewF;
LINK                    RDFRet          ReReviewF Review1 DrawingSet;

LINK                    RRF             ReworkRevF ReReviewF;
LINK                    RRFRet          ReReviewF ReworkRevF;

/ Links for reporting information
LINK                    R1              Complete Report;
LINK                    R2              Report Complete1;
/**********************************************************************************************
/* Definition of global variables and programing objects

FILTER ArchRevF         DrawingSet 'ArchR==0';
FILTER StructRevF       DrawingSet 'StructR==0';
FILTER MechRevF         DrawingSet 'MechR==0';
FILTER ElectRevF        DrawingSet 'ElectR==0';
FILTER FLSRevF                  DrawingSet 'FLSR==0';
FILTER ReworkF                  DrawingSet
'ArchR==1&StructR==1&MechR==1&ElectR==1&FLSR==1';
```

```
FILTER DrawingAtFront DrawingSet 'RandomNo==DrawingTable.RandomNo.MinVal';
FILTER DrawingAtFront1 DrawingSet 'ProjNo==Complete.ProjNo.MinVal';

DISCIPLINE DrawingTable DiscipProp;
DISCIPLINE Complete  DiscipProp1;

FILTER ArchPerF        ReviewPer 'Arch==100';
FILTER StructPerF      ReviewPer 'Struct==200';
FILTER MechPerF        ReviewPer 'Mech==300';
FILTER ElectPerF       ReviewPer 'Elect==400';
FILTER FLSPerF                 ReviewPer 'FLS==500';

/ Create Filters to direct correctly assigned rework to its corresponding review;
FILTER ReworkRevFA DrawingSet 'RevError==100';
FILTER ReworkRevFS DrawingSet 'RevError==200';
FILTER ReworkRevFM DrawingSet 'RevError==300';
FILTER ReworkRevFE DrawingSet 'RevError==400';
FILTER ReworkRevFF DrawingSet 'RevError==500';
/*************************************************************************************************
/* Statements to assist in the definition of attributes of Projects and its related links
/*************************************************************************************************
/* Entry of resources into Projects

/ This step creates the number of drawing sets that will be loaded into the system. Three types of
/ projects will be loaded into the system to represent small, medium, or large projects either new
/ construction or renovated.

INIT Projects Type1proj Type1;
INIT Projects Type2proj Type2;
INIT Projects Type3proj Type3;
INIT Projects Type4proj Type4;
INIT Projects Type5proj Type5;

INIT ArchPer    NoArchRev     Arch;
INIT StructPer  NoStrucRev    Struct;
INIT MechPer    NoMechRev     Mech;
INIT ElectPer   NoElecRev     Elect;
INIT FLSPer     NoFLSRev      FLS;

INIT ReworkRevA       NoArchRev     Arch;
INIT ReworkRevS       NoStrucRev    Struct;

INIT ReworkRevM       NoMechRev     Mech;
INIT ReworkRevE       NoElecRev     Elect;
INIT ReworkRevF       NoFLSRev      FLS;
/*************************************************************************************************
/* Startup of Initialize

ONDRAW DS1            ASSIGN RandomNo RandomNumber+Size;

ONDRAW DS1            ASSIGN ProjNo ResNum;

DURATION              Initialize '0';
/*************************************************************************************************

/* Termination of Initialize
```

/ This initializes the properties of each of the drawings that flow through the model. Each
ONRELEASE DS2 ASSIGN ArchR 0;

ONRELEASE DS2 ASSIGN StructR 0;
ONRELEASE DS2 ASSIGN MechR 0;
ONRELEASE DS2 ASSIGN ElectR 0;
ONRELEASE DS2 ASSIGN FLSR 0;
ONRELEASE DS2 ASSIGN Reworked 0;

/Turn on the following two print statements to verify random generation of projects to load into
/the system.

/ ONRELEASE DS2 PRINT StdOutput "Proj No. \t%5.1f" ResNum;
/ ONRELEASE DS2 PRINT StdOutput "\tRandom No Assign \t%5.4f\n" RandomNo;
/*****************************************************************************************************
/* Entry of resources into DrawingTable
/*****************************************************************************************************
/* Statements to assist in the definition of attributes of ArchRev and its related links
/*****************************************************************************************************
/* Startup of ArchRev

/ This criterion will only pull drawings where the ArchR is less than one. This step ensures that
/ the drawings will only be reviewed once by the architect before a rework decision is made.

/ This step will only pull a drawing set to review if there is one or more drawings in the queue

ENOUGH ArchDS 'DrawingTable.ArchRevF.Count>=1';

DRAWWHERE ArchDS 'ArchR==0&DrawingAtFront';

/ ONDRAW ArchDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW ArchDS PRINT StdOutput "\tin ArchRev at\t%5.1f\n" SimTime;

ONDRAW ArchDS ASSIGN ArchTime SimTime;

/ ONDRAW ArchDS PRINT StdOutput "\tin ArchRev at\t%5.1f\n" ArchTime;

/ This criterion requires one architect to be available to review the drawings set.

ENOUGH AP1 'ArchPer.CurCount>= 1';

/ This step lists the duration of the architectural review which will be a normal distribution.
/ This step will expand to incorporate three types of review, small, medium and large. The
/ durations will be taken from the database provided.

DURATION ArchRev
'Normal[ArchRev.DrawingSet.ArchMu,ArchRev.DrawingSet.ArchSD]';
/*****************************************************************************************************
/* Termination of ArchRev

/ This resets the value to one once the drawing has been reviewed by the architect.

ONRELEASE ArchDSRet ASSIGN ArchR ArchR+1;

```
/ ONDRAW ArchDS       PRINT StdOutput “======= Arch Filter Count =%5.1f\n”
DrawingTable.ArchRevF.Count;

/ ONDRAW StructDS PRINT StdOutput “======= Struct Filter Count =%5.1f\n”
DrawingTable.StructRevF.Count;

/ ONDRAW MechDS PRINT StdOutput “======= Mech Filter Count =%5.1f\n”
DrawingTable.MechRevF.Count;

/ ONDRAW ElectDS PRINT StdOutput “======= Elect Filter Count =%5.1f\n”
DrawingTable.ElectRevF.Count;

/ ONDRAW FLSDS PRINT StdOutput “======= FLS Filter Count =%5.1f\n”
DrawingTable.FLSRevF.Count;

/ ONDRAW RD1 PRINT StdOutput “======= Rework Filter Count =%5.1f\n”
DrawingTable.Rework.Count;
/***************************************************************************************************
/* Startup of StructRev

/ The following two criteria require that at least one drawing be available for review and that a
/ structural design reviewer is available.

ENOUGH                    StructDS ‘DrawingTable.StructRevF.Count>0’;

DRAWWHERE                 StructDS ‘StructR==0&DrawingAtFront’;

/ ONDRAW StructDS PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONDRAW StructDS PRINT StdOutput “\tin StructRev at\t%5.1f\n” SimTime;

ONDRAW StructDS ASSIGN StructTime SimTime;

/ ONDRAW StructDS PRINT StdOutput “\tin StructRev at\t%5.1f\n” StructTime;

ENOUGH                            SP1 ‘StructPer.CurCount>=1’;

/ This criteria will only draw a project if it hasn’t been reviewed by a structural design reviewer

/ This step lists the duration of the structural review which will be a normal distribution.

DURATION                  StructRev
‘Normal[StructRev.DrawingSet.StructMu,StructRev.DrawingSet.StructSD]’;
/***************************************************************************************************
/* Termination of StructRev

ONRELEASE StructDSRet ASSIGN StructR StructR+1;
/***************************************************************************************************
/* Startup of MechRev

/ The following two criteria require that at least one drawing be available for review and that a
/ mechanical design reviewer is available.

/ ENOUGH                  MechDS ‘DrawingTable.Type1.Count>=1’;

ENOUGH                    MechDS ‘DrawingTable.MechRevF.Count>=1’;
```

```
DRAWWHERE          MechDS 'MechR==0&DrawingAtFront';

/ ONDRAW MechDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW MechDS PRINT StdOutput "\tin MechRev at\t%5.1f\n" SimTime;

ONDRAW MechDS ASSIGN MechTime SimTime;

/ ONDRAW MechDS PRINT StdOutput "\tin MechRev at\t%5.1f\n" MechTime;

ENOUGH                    MP1 'MechPer.CurCount>=1';

/ This criteria will only draw a project if it hasn't been reviewed by a mechanical design reviewer

/ This step lists the duration of the mechanical review which will be a normal distribution.


DURATION           MechRev
'Normal[MechRev.DrawingSet.MechMu,MechRev.DrawingSet.MechSD]';
/*****************************************************************************************************
/* Termination of MechRev

ONRELEASE MechDSRet ASSIGN MechR MechR+1;
/*****************************************************************************************************
/* Startup of ElectRev

/ The following two criteria require that at least one drawing be available for review and that a
/ electrical design reviewer is available.

/ ENOUGH           ElectDS 'DrawingTable.Type1.Count>=1';

ENOUGH             ElectDS 'DrawingTable.ElectRevF.Count>=1';

DRAWWHERE          ElectDS 'ElectR==0&DrawingAtFront';

/ ONDRAW ElectDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW ElectDS PRINT StdOutput "\tin ElectRev at\t%5.1f\n" SimTime;

ONDRAW ElectDS ASSIGN ElectTime SimTime;

/ ONDRAW ElectDS PRINT StdOutput "\tin ElectRev at\t%5.1f\n" ElectTime;

ENOUGH                    EP1 'ElectPer.CurCount>=1';

/ This criteria will only draw a project if it hasn't been reviewed by a electrical design reviewer

/ This step lists the duration of the electrical review which will be a normal distribution.

DURATION           ElectRev
'Normal[ElectRev.DrawingSet.ElectMu,ElectRev.DrawingSet.ElectSD]';
/*****************************************************************************************************
/* Termination of ElectRev
```

```
ONRELEASE ElectDSRet ASSIGN ElectR ElectR+1;
/*****************************************************************************************************
/* Startup of FLSRev

/ The following two criteria require that at least one drawing be available for review and that a
/ fire, life, and safety design reviewer is available.

/ ENOUGH                    FLSDS 'DrawingTable.Type1.Count >=1';

ENOUGH                      FLSDS 'DrawingTable.FLSRevF.Count>=1';

DRAWWHERE          FLSDS 'FLSR==0&DrawingAtFront';

/ ONDRAW FLSDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW FLSDS PRINT StdOutput "\tin FLSRev at\t%5.1f\n" SimTime;

ONDRAW FLSDS ASSIGN FLSTime SimTime;

/ ONDRAW FLSDS PRINT StdOutput "\tin FLSRev at\t%5.1f\n" FLSTime;

ENOUGH                      FP1 'FLSPer.CurCount >= 1';

/ This criteria will only draw a project if it hasn't been reviewed by a fire, life, and safety
/ design reviewer

/ This step lists the duration of the fire, life, and safety review which will be a normal
/ distribution.


DURATION           FLSRev
'Normal[FLSRev.DrawingSet.FLSMu,FLSRev.DrawingSet.FLSSD]';
/*****************************************************************************************************
/* Termination of FLSRev

ONRELEASE FLSDSRet ASSIGN FLSR FLSR+1;
/*****************************************************************************************************
/* Startup of Review

ENOUGH RD1 'DrawingTable.ReworkF.Count>=1';

DRAWWHERE RD1 'ArchR==1&StructR==1&MechR==1&ElectR==1&FLSR==1';

ONDRAW RD1 ReworkFactor 1;

ONDRAW RD1 Reworked 0;

DURATION Review '0';
/*****************************************************************************************************
/* Termination of Review
/*****************************************************************************************************
/* Startup of Review1

DURATION Review1 '0';
/*****************************************************************************************************
/* Termination of Review1
```

```
/* Rework factor, set to 1 if drawingset has never been repaired and to 2 if it has

STRENGTH RD3 100-Review1.DrawingSet.r/Review1.DrawingSet.ReworkFactor;

STRENGTH RD4 'Review1.DrawingSet.r/Review1.DrawingSet.ReworkFactor';
/*************************************************************************************************
/* Startup of OwnerRework

ENOUGH RD5 'Rework.ReworkF.Count>=1';

/ ONFLOW RD3 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONFLOW RD3 PRINT StdOutput "\tCOMPLETE at \t%5.1f" SimTime;

/ ONFLOW RD3 PRINT StdOutput "\tReworked \t%5.0f \tTime(s)\t" Reworked;

ONFLOW RD3 ASSIGN CompleteTime SimTime;

/ONFLOW RD3 COLLECT PermitTime CompleteTime-ArchTime;
/ONFLOW RD3 COLLECT PermitTime CompleteTime-StructTime;
/ONFLOW RD3 COLLECT PermitTime CompleteTime-MechTime;
/ONFLOW RD3 COLLECT PermitTime CompleteTime-ElectTime;
/ONFLOW RD3 COLLECT PermitTime CompleteTime-FLSTime;

/ONFLOW RD3 PRINT StdOutput "Approval Time \t%5.1f\t,\t" PermitTime.MaxVal;

/ONFLOW RD3 PRINT StdOutput "Owner Rework Time \t%5.1f\n" OwnerReworkTotal;

/ ONFLOW RD3 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONFLOW RD3 PRINT StdOutput "\t(Arch) Comp Time \t%5.1f\n" CompleteTime-ArchTime;

/ ONFLOW RD3 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONFLOW RD3 PRINT StdOutput "\t(Struct) Comp Time \t%5.1f\n" CompleteTime-StructTime;

/ ONFLOW RD3 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONFLOW RD3 PRINT StdOutput "\t(Mech) Comp Time \t%5.1f\n" CompleteTime-MechTime;

/ ONFLOW RD3 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONFLOW RD3 PRINT StdOutput "\t(Elect) Comp Time \t%5.1f\n" CompleteTime-ElectTime;

/ ONFLOW RD3 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONFLOW RD3 PRINT StdOutput "\t(FLS) Comp Time \t%5.1f\n" CompleteTime-FLSTime;

ONDRAW RD5 ASSIGN OwnerStart SimTime;

ONDRAW RD5 ASSIGN RevError RevAssignError;

DURATION OwnerRework
'Normal[OwnerRework.DrawingSet.ORewMu,OwnerRework.DrawingSet.ORewSD]';
```

```
/Turn on these print statements to show the error assigned and the rework factor.

/ ONRELEASE RD6 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONRELEASE RD6 PRINT StdOutput "\tAssign Err No. \t%5.0f" RevError;

/ ONRELEASE RD6 PRINT StdOutput "\tRework Percent \t%5.1f\n" 'r/ReworkFactor';
/**********************************************************************************************
/* Termination of OwnerRework

ONRELEASE RD6 ASSIGN OwnerEnd SimTime;

ONRELEASE RD6 ASSIGN OwnerReworkTotal OwnerReworkTotal+(OwnerEnd-OwnerStart);

/ ONRELEASE RD6 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONRELEASE RD6 PRINT StdOutput "\tOwner Rework Time \t%5.1f\n" OwnerReworkTotal;
/**********************************************************************************************
/* Startup of ReReviewA

ENOUGH RDA 'Resubmit.ReworkRevFA.Count>=1';

DRAWWHERE RDA 'RevError==100';

/Turn on the print statement to check the reviewer assigned.

/ ONDRAW RRA PRINT StdOutput "\t\t\t\t\tReview assign \t%5.0f\n" Type;

DURATION ReReviewA 'Normal
[ReReviewA.DrawingSet.RRevAMu,ReReviewA.DrawingSet.RRevASD]';
/**********************************************************************************************
/* Termination of ReReviewA

ONRELEASE RDARet ASSIGN Reworked Reworked+1;

ONRELEASE RDARet ASSIGN ReworkFactor ReworkFactor+1;

ONRELEASE RDARet ASSIGN RevError 0;

/ ONRELEASE RDARet PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONRELEASE RDARet PRINT StdOutput "\tREWORKED \t\t%5.1f \tTime(s)\n" Reworked;
/**********************************************************************************************
/* Startup of ReReviewS

ENOUGH RDS 'Resubmit.ReworkRevFS.Count>=1';

DRAWWHERE RDS 'RevError==200';

/Turn on the print statement to check the reviewer assigned.

/ ONDRAW RRS PRINT StdOutput "\t\t\t\t\tReview assign \t%5.0f\n" Type;

DURATION ReReviewS 'Normal
[ReReviewS.DrawingSet.RRevSMu,ReReviewS.DrawingSet.RRevSSD]';
```

```
/***********************************************************************************************
/* Termination of ReReviewS

ONRELEASE RDSRet ASSIGN Reworked Reworked+1;

ONRELEASE RDSRet ASSIGN ReworkFactor ReworkFactor+1;

ONRELEASE RDSRet ASSIGN RevError 0;

/ ONRELEASE RDSRet PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONRELEASE RDSRet PRINT StdOutput “\tREWORKED \t\t%5.1f \tTime(s)\n” Reworked;
/***********************************************************************************************
/* Startup of ReReviewM

ENOUGH RDM ‘Resubmit.ReworkRevFM.Count>=1’;

DRAWWHERE RDM ‘RevError==300’;

/Turn on the print statement to check the reviewer assigned.

/ ONDRAW RRM PRINT StdOutput “\t\t\t\t\tReview assign \t%5.0f\n” Type;

DURATION ReReviewM ‘Normal
[ReReviewM.DrawingSet.RRevMMu,ReReviewM.DrawingSet.RRevMSD]’;
/***********************************************************************************************
/* Termination of ReReviewM

ONRELEASE RDMRet ASSIGN Reworked Reworked+1;

ONRELEASE RDMRet ASSIGN ReworkFactor ReworkFactor+1;

ONRELEASE RDMRet ASSIGN RevError 0;

/ ONRELEASE RDMRet PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONRELEASE RDMRet PRINT StdOutput “\tREWORKED \t\t%5.1f \tTime(s)\n” Reworked;
/***********************************************************************************************
/* Startup of ReReviewE

ENOUGH RDE ‘Resubmit.ReworkRevFE.Count>=1’;

DRAWWHERE RDE ‘RevError==400’;

/Turn on the print statement to check the reviewer assigned.

/ ONDRAW RRE PRINT StdOutput “\t\t\t\t\tReview assign \t%5.0f\n” Type;

DURATION ReReviewE ‘Normal
[ReReviewE.DrawingSet.RRevEMu,ReReviewE.DrawingSet.RRevESD]’;
/***********************************************************************************************
/* Termination of ReReviewE

ONRELEASE RDERet ASSIGN Reworked Reworked+1;

ONRELEASE RDERet ASSIGN ReworkFactor ReworkFactor+1;
```

```
ONRELEASE RDERet ASSIGN RevError 0;

/ ONRELEASE RDERet PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONRELEASE RDERet PRINT StdOutput “\tREWORKED \t\t%5.1f \tTime(s)\n” Reworked;
/***********************************************************************************************
/* Startup of ReReviewF

ENOUGH RDF ‘Resubmit.ReworkRevFF.Count>=1’;

DRAWWHERE RDF ‘RevError==500’;

/Turn on the print statement to check the reviewer assigned.

/ ONDRAW RRF PRINT StdOutput “\t\t\t\t\tReview assign \t%5.0f\n” Type;

DURATION ReReviewF ‘Normal
[ReReviewF.DrawingSet.RRevFMu,ReReviewF.DrawingSet.RRevFSD]’;
/***********************************************************************************************
/* Termination of ReReviewF

ONRELEASE RDFRet ASSIGN Reworked Reworked+1;

ONRELEASE RDFRet ASSIGN ReworkFactor ReworkFactor+1;

ONRELEASE RDFRet ASSIGN RevError 0;

/ ONRELEASE RDFRet PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONRELEASE RDFRet PRINT StdOutput “\tREWORKED \t\t%5.1f \tTime(s)\n” Reworked;
/***********************************************************************************************
/* Startup of Report

ENOUGH R1
‘Complete.ReworkF.Count==Type1proj+Type2proj+Type3proj+Type4proj+Type5proj’;

/ ENOUGH R1 ‘Complete.ReworkF.Count==10’;

DRAWWHERE R1 ‘DrawingAtFront1’;

DRAWUNTIL R1
‘Report.DrawingSet.Count==Type1proj+Type2proj+Type3proj+Type4proj+Type5proj’ ;

DURATION Report 0;

ONRELEASE R2 COLLECT PermitTime CompleteTime-ArchTime;
ONRELEASE R2 COLLECT PermitTime CompleteTime-StructTime;
ONRELEASE R2 COLLECT PermitTime CompleteTime-MechTime;
ONRELEASE R2 COLLECT PermitTime CompleteTime-ElectTime;
ONRELEASE R2 COLLECT PermitTime CompleteTime-FLSTime;

ONRELEASE R2 PRINT StdOutput “Proj No.\t%4.0f” ResNum;

ONRELEASE R2 PRINT StdOutput “\tReworked\t%2.0f\tTime(s)\t” Reworked;
```

```
ONRELEASE R2 PRINT StdOutput “Approval Time\t%5.1f\t,\t” PermitTime.MaxVal;

ONRELEASE R2 PRINT StdOutput “Owner Rework Time\t%5.1f\t,\n” OwnerReworkTotal;
/*************************************************************************************************
/* Termination of Report
/*************************************************************************************************
/* Entry of resources into OArchPer

INIT OArchPer 10;
/*************************************************************************************************

/* Initialization of Queues, Running the Simulation, Presenting Results

SIMULATEUNTIL ‘Complete1.Type1.Count==Type1proj&Complete1.Type2.Count==Type2proj&

        Complete1.Type3.Count==Type3proj&Complete1.Type4.Count==Type4proj&
                                Complete1.Type5.Count==Type5proj’;
```

Model 2

```
/***************************************************************************************************
/* Stroboscope source file generated from Visio drawing C:\Documents and Settings\Peter
Feng\Desktop\Berkeley Working Folder\PhD Research\4. Case Studies\2. OSHPD\1. OSHPD
Simulation (9 Jul 08).vsd
/***************************************************************************************************
VARIABLE Type1proj              50;
VARIABLE Type2proj              100;
VARIABLE Type3proj              35;
VARIABLE Type4proj              20;
VARIABLE Type5proj              0;

VARIABLE NoArchRev              1;
VARIABLE NoStrucRev             1;
VARIABLE NoMechRev              1;
VARIABLE NoElecRev              1;
VARIABLE NoFLSRev               1;

VARIABLE RevAssignError         'Rnd[]          <= 1/5 ? 100:
                                                 LastRnd[]      <= 2/5 ? 200:
                                                 LastRnd[]      <= 3/5 ? 300:
                                                 LastRnd[]      <= 4/5 ? 400: 500';

VARIABLE RandomNumber           'Rnd[]';

MVAVGCOLLECTOR PermitTime 5;
/***************************************************************************************************
/* Definition of resource types

/ Define the drawing sets as a resource. This will be the primary resource that flows through the
/ model. With each drawing set resource a number of characteristics will be assigned. These
/ characteristics will track how many times a drawing is reviewed and will serve as a counter.
/ Multiple subtypes of drawing set will be defined. Three different sizes will be established
/ to represent the actual types of drawings. Small, medium and large projects will be defined
/ Each of the sizes of drawings can represent either new construction or renovation.

CHARTYPE     DrawingSet     Size    ArchMu          ArchSD          StructMu
          StructSD          MechMu          MechSD          ElectMu         ElectSD         FLSMu
          FLSSD             r               OReWMu          OReWSD          RRevAMu
          RRevASD            RRevSMu        RRevSSD         RRevMMu         RRevMSD
          RRevEMu           RRevESD         RRevFMu         RRevFSD         ; /DR
/==========================================================================================
SUBTYPE DrawingSet  Type1   1       1.17            0.17            1.85
          0.4               1.07            0.05            1.07            0.05            1.36
          0.21              82        5             1               1.44
          0.42              1.17            0.09            1.39            0.25
          1.03              0.03            1.34            0.19            ;
/--------------------------------------------------
SUBTYPE DrawingSet  Type2   10      1.66            0.26            2.59
          0.4               3.79            1.17            0.07            1.38            0.22
          93                10              2               1.68            0.26
          2.3               0.49            1.17            0.2             1.07
          0.04              1.96            0.32                            ;
/--------------------------------------------------
```

```
SUBTYPE DrawingSet  Type3   100     2.85            0.7             8.32
          1.1             4.37            0.8             4.39            1.26            4.0
          0.76            99              20              3               1.6
          0.29            6.04            0.92            1.82            0.45
          1.44            0.2             4.19            1.17            ;
/--------------------------------------------------
SUBTYPE DrawingSet  Type4   100     8.38            1.82            21.5
          6.25            10.9            2.38            8.27            1.94            18.2
          3.43            88              70              5               4.05
          1.53            10.8            2.9             4.8             1.51
          2.7             0.72            7.57            1.8             ;
/--------------------------------------------------
SUBTYPE DrawingSet  Type5   100     8.38            1.82            21.5
          6.25            10.9            2.38            8.27            1.94            18.2
          3.43            88              70              5               4.05
          1.53            10.8            2.9             4.8             1.51
          2.7             0.72            7.57            1.8             ;
/--------------------------------------------------

SAVEPROPS   DrawingSet ArchR StructR MechR ElectR FLSR RevError;
SAVEPROPS   DrawingSet RandomNo TotNoRev EntryNumber;
SAVEPROPS   DrawingSet Reworked;
SAVEPROPS   DrawingSet ReworkPercent ReworkFactor;
SAVEPROPS   DrawingSet ArchTime StructTime MechTime ElectTime FLSTime CompleteTime;
SAVEPROPS   DrawingSet OwnerStart OwnerEnd OwnerReworkTotal;
SAVEPROPS   DrawingSet ProjNo;

VARPROP             DrawingSet DiscipProp RandomNo;
VARPROP             DrawingSet DiscipProp1          ProjNo;

CHARTYPE    ReviewPer                                   Type; /RP
/==========================================================================
SUBTYPE             ReviewPer           Arch            100;
SUBTYPE             ReviewPer           Struct          200;
SUBTYPE             ReviewPer           Mech            300;
SUBTYPE             ReviewPer           Elect           400;
SUBTYPE             ReviewPer           FLS                     500;
/--------------------------------------------------

/ Define five resources that represent the design review personnel.

GENTYPE             OArchPerson; /AP
/***************************************************************************************************
/* General section for problem parameters
/***************************************************************************************************
/* Definition of network nodes

/ Creates a queue that will hold characterized resources

QUEUE               Projects DrawingSet;

/ Combi that initializes each drawings set so the characteristics are set to zero

COMBI               Initialize;

/ Creates a queue that represents an area to hold drawings when waiting to be worked on by the
```

```
/ design review specialist

QUEUE                   DrawingTable DrawingSet;

/ Series of combi that represent the actual review conducted by the design specialist. The
process
/ times associated with each combi was taken from database provided by OSHPD

COMBI                   ArchRev;

COMBI                   StructRev;
COMBI                   MechRev;
COMBI                   ElectRev;
COMBI                   FLSRev;

/ Combi that reviews each drawings will only draw from the Drawing Table if each resource has
/ 1 for each of the review characteristics
COMBI                   Review;
NORMAL                          Review1;
COMBI                   OwnerRework;

/Combi for the rereview process, will be sent drawings from a random calculation of who is
assigned error
COMBI                   ReReviewA;
COMBI                   ReReviewS;
COMBI                   ReReviewM;
COMBI                   ReReviewE;
COMBI                   ReReviewF;

/ Creates a series of queues that hold the design review specialist resource. This resource is the
/ one of the limiting factors that can throttle the speed of the review. With more resources, more
/ drawings can be reviewed.

QUEUE                   ArchPer ReviewPer;
QUEUE                   StructPer ReviewPer;
QUEUE                   MechPer ReviewPer;
QUEUE                   ElectPer ReviewPer;
QUEUE                   FLSPer ReviewPer;

QUEUE                   OArchPer OArchPerson;

/ Create Queue for rework decision
QUEUE                   Complete DrawingSet;
QUEUE                   Rework DrawingSet;
QUEUE                   Resubmit DrawingSet;


/ Create queues for characterized resources, reviewers for each discipline
/ QUEUE                         ReworkRevA ReviewPer;
/ QUEUE                         ReworkRevS ReviewPer;
/ QUEUE                         ReworkRevM ReviewPer;
/ QUEUE                         ReworkRevE ReviewPer;
/ QUEUE                         ReworkRevF ReviewPer;

/ Create queue for reporting information
QUEUE                           Complete1 DrawingSet;
```

```
COMBI                   Report;
/***************************************************************************************************
/* Definition of forks

FORK                    ReworkDecision DrawingSet;
/***************************************************************************************************
/* Definition of network Links

/ Created below are the links for the model system. The links with DS in the name represent the
flow
/ of drawing set resources.
/ The links with AP, SP, MP, EP and FP represent the flow of design review personnel.

LINK                    DS1 Projects Initialize;
LINK                    DS2 Initialize DrawingTable;
LINK                    ArchDS DrawingTable ArchRev;
LINK                    ArchDSRet ArchRev DrawingTable;
LINK                    StructDS DrawingTable StructRev;

LINK                    StructDSRet StructRev DrawingTable;
LINK                    MechDS DrawingTable MechRev;
LINK                    MechDSRet MechRev DrawingTable;
LINK                    ElectDS DrawingTable ElectRev;
LINK                    ElectDSRet ElectRev DrawingTable;
LINK                    FLSDS DrawingTable FLSRev;
LINK                    FLSDSRet FLSRev DrawingTable;

LINK                    AP1 ArchPer ArchRev;

LINK                    APRet ArchRev ArchPer;
LINK                    SP1 StructPer StructRev;

LINK                    SPRet StructRev StructPer;
LINK                    MP1 MechPer MechRev;
LINK                    MPRet MechRev MechPer;
LINK                    EP1 ElectPer ElectRev;
LINK                    EPRet ElectRev ElectPer;
LINK                    FP1 FLSPer FLSRev;
LINK                    FPRet FLSRev FLSPer;

LINK                    RD1 DrawingTable Review;
LINK                    RD1A Review Review1 DrawingSet;

LINK                    RD2 Review1 ReworkDecision;
LINK                    RD3     ReworkDecision Complete;
LINK                    RD4 ReworkDecision Rework;
LINK                    RD5 Rework OwnerRework;
LINK                    RD6 OwnerRework Resubmit;

LINK                    OR1 OArchPer OwnerRework;
LINK                    OR2 OwnerRework OArchPer;

/ Architect ReReview Links
LINK                    RDA     Resubmit ReReviewA;
LINK                    RDARet          ReReviewA Review1 DrawingSet;
```

```
LINK                    RRA     ArchPer ReReviewA;
LINK                    RRARet          ReReviewA ArchPer;

/ Structural ReReview Links
LINK                    RDS     Resubmit ReReviewS;
LINK                    RDSRet          ReReviewS Review1 DrawingSet;

LINK                    RRS             StructPer ReReviewS;
LINK                    RRSRet          ReReviewS StructPer;

/ Mechanical ReReview Links
LINK                    RDM     Resubmit ReReviewM;
LINK                    RDMRet          ReReviewM Review1 DrawingSet;

LINK                    RRM             MechPer ReReviewM;
LINK                    RRMRet          ReReviewM MechPer;

/ Electrical ReReview Links
LINK                    RDE     Resubmit ReReviewE;
LINK                    RDERet          ReReviewE Review1 DrawingSet;

LINK                    RRE             ElectPer ReReviewE;
LINK                    RRERet          ReReviewE ElectPer;

/ FLS ReReview Links
LINK                    RDF     Resubmit ReReviewF;
LINK                    RDFRet          ReReviewF Review1 DrawingSet;

LINK                    RRF             FLSPer ReReviewF;
LINK                    RRFRet          ReReviewF FLSPer;

/ Links for reporting information
LINK                    R1              Complete Report;
LINK                    R2              Report Complete1;
/**************************************************************************************************
/* Definition of global variables and programing objects

FILTER ArchRevF DrawingSet ‘ArchR==0’;
FILTER StructRevF DrawingSet ‘StructR==0’;
FILTER MechRevF DrawingSet ‘MechR==0’;
FILTER ElectRevF DrawingSet ‘ElectR==0’;
FILTER FLSRevF DrawingSet ‘FLSR==0’;
FILTER ReworkF DrawingSet ‘ArchR==1&StructR==1&MechR==1&ElectR==1&FLSR==1’;

FILTER DrawingAtFront DrawingSet ‘RandomNo==DrawingTable.RandomNo.MinVal’;
FILTER DrawingAtFront1 DrawingSet ‘ProjNo==Complete.ProjNo.MinVal’;

DISCIPLINE DrawingTable DiscipProp;
DISCIPLINE Complete  DiscipProp1;

FILTER ArchPerF ReviewPer ‘Arch==100’;
FILTER StructPerF ReviewPer ‘Struct==200’;
FILTER MechPerF ReviewPer ‘Mech==300’;
FILTER ElectPerF ReviewPer ‘Elect==400’;
FILTER FLSPerF ReviewPer ‘FLS==500’;
```

```
/ Create Filters to direct correctly assigned rework to its corresponding review;
FILTER ReworkRevFA DrawingSet ‘RevError==100’;
FILTER ReworkRevFS DrawingSet ‘RevError==200’;
FILTER ReworkRevFM DrawingSet ‘RevError==300’;
FILTER ReworkRevFE DrawingSet ‘RevError==400’;
FILTER ReworkRevFF DrawingSet ‘RevError==500’;
/****************************************************************************************************
/* Statements to assist in the definition of attributes of Projects and its related links
/****************************************************************************************************
/* Entry of resources into Projects

/ This step creates the number of drawing sets that will be loaded into the system. Three types of
/ projects will be loaded into the system to represent small, medium, or large projects either new
/ construction or renovated.

INIT Projects Type1proj Type1;
INIT Projects Type2proj Type2;
INIT Projects Type3proj Type3;
INIT Projects Type4proj Type4;

INIT ArchPer     NoArchRev     Arch;
INIT StructPer   NoStrucRev    Struct;
INIT MechPer     NoMechRev     Mech;
INIT ElectPer    NoElecRev     Elect;
INIT FLSPer      NoFLSRev      FLS;

/ INIT ReworkRevA      1        Arch;
/ INIT ReworkRevS      1        Struct;

/ INIT ReworkRevM      1        Mech;
/ INIT ReworkRevE      1        Elect;
/ INIT ReworkRevF      1        FLS;
/****************************************************************************************************
/* Startup of Initialize

ONDRAW DS1           ASSIGN RandomNo RandomNumber+Size;

ONDRAW DS1           ASSIGN ProjNo ResNum;

DURATION             Initialize ‘0’;
/****************************************************************************************************
/* Termination of Initialize

/ This initializes the properties of each of the drawings that flow through the model. Each
ONRELEASE DS2 ASSIGN ArchR 0;

ONRELEASE DS2 ASSIGN StructR 0;
ONRELEASE DS2 ASSIGN MechR 0;
ONRELEASE DS2 ASSIGN ElectR 0;
ONRELEASE DS2 ASSIGN FLSR 0;
ONRELEASE DS2 ASSIGN Reworked 0;

/Turn on the following two print statements to verify random generation of projects to load into
/the system.

/ ONRELEASE DS2 PRINT StdOutput “Proj No. \t%5.1f” ResNum;
```

```
/ ONRELEASE DS2 PRINT StdOutput "\tRandom No Assign \t%5.4f\n" RandomNo;

/ ONRELEASE DS2 PRINT StdOutput "Proj No. \t%5.1f" ResNum;
/ ONRELEASE DS2 PRINT StdOutput "\tRandom No Assign \t%5.0f\n" ProjNo;
/**************************************************************************************************
/* Entry of resources into DrawingTable
/**************************************************************************************************
/* Statements to assist in the definition of attributes of ArchRev and its related links
/**************************************************************************************************
/* Startup of ArchRev

/ This criterion will only pull drawings where the ArchR is less than one. This step ensures that
/ the drawings will only be reviewed once by the architect before a rework decision is made.

/ This step will only pull a drawing set to review if there is one or more drawings in the queue

ENOUGH          ArchDS 'DrawingTable.ArchRevF.Count>=1';

DRAWWHERE       ArchDS 'ArchR==0&DrawingAtFront';

/ ONDRAW ArchDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW ArchDS PRINT StdOutput "\tin ArchRev at\t%5.1f\n" SimTime;

ONDRAW ArchDS ASSIGN ArchTime SimTime;

/ This criterion requires one architect to be available to review the drawings set.

ENOUGH                  AP1 'ArchPer.CurCount>= 1';

/ This step lists the duration of the architectural review which will be a normal distribution.
/ This step will expand to incorporate three types of review, small, medium and large. The
/ durations will be taken from the database provided.

DURATION        ArchRev
'Normal[ArchRev.DrawingSet.ArchMu,ArchRev.DrawingSet.ArchSD]';
/**************************************************************************************************
/* Termination of ArchRev

/ This resets the value to one once the drawing has been reviewed by the architect.


ONRELEASE ArchDSRet ASSIGN ArchR ArchR+1;

/ ONDRAW ArchDS   PRINT StdOutput "======= Arch Filter Count =%5.1f\n"
DrawingTable.ArchRevF.Count;

/ ONDRAW StructDS PRINT StdOutput "======= Struct Filter Count =%5.1f\n"
DrawingTable.StructRevF.Count;

/ ONDRAW MechDS PRINT StdOutput "======= Mech Filter Count =%5.1f\n"
DrawingTable.MechRevF.Count;

/ ONDRAW ElectDS PRINT StdOutput "======= Elect Filter Count =%5.1f\n"
DrawingTable.ElectRevF.Count;
```

```
/ ONDRAW FLSDS PRINT StdOutput "======= FLS Filter Count =%5.1f\n"
DrawingTable.FLSRevF.Count;

/ ONDRAW RD1 PRINT StdOutput "======= Rework Filter Count =%5.1f\n"
DrawingTable.Rework.Count;
/*************************************************************************************************
/* Startup of StructRev

/ The following two criteria require that at least one drawing be available for review and that a
/ structural design reviewer is available.

ENOUGH             StructDS 'DrawingTable.StructRevF.Count>0';

DRAWWHERE          StructDS 'StructR==0&DrawingAtFront';

/ ONDRAW StructDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW StructDS PRINT StdOutput "\tin StructRev at\t%5.1f\n" SimTime;

ONDRAW StructDS ASSIGN StructTime SimTime;

ENOUGH                   SP1 'StructPer.CurCount>=1';

/ This criteria will only draw a project if it hasn't been reviewed by a structural design reviewer

/ This step lists the duration of the structural review which will be a normal distribution.

DURATION           StructRev
'Normal[StructRev.DrawingSet.StructMu,StructRev.DrawingSet.StructSD]';
/*************************************************************************************************
/* Termination of StructRev

ONRELEASE StructDSRet ASSIGN StructR StructR+1;
/*************************************************************************************************
/* Startup of MechRev

/ The following two criteria require that at least one drawing be available for review and that a
/ mechanical design reviewer is available.

/ ENOUGH           MechDS 'DrawingTable.Type1.Count>=1';

ENOUGH             MechDS 'DrawingTable.MechRevF.Count>=1';

DRAWWHERE          MechDS 'MechR==0&DrawingAtFront';

/ ONDRAW MechDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW MechDS PRINT StdOutput "\tin MechRev at\t%5.1f\n" SimTime;

ONDRAW MechDS ASSIGN MechTime SimTime;

ENOUGH                   MP1 'MechPer.CurCount>=1';

/ This criteria will only draw a project if it hasn't been reviewed by a mechanical design reviewer
```

```
/ This step lists the duration of the mechanical review which will be a normal distribution.

DURATION              MechRev
'Normal[MechRev.DrawingSet.MechMu,MechRev.DrawingSet.MechSD]';
/*************************************************************************************************
/* Termination of MechRev

ONRELEASE MechDSRet ASSIGN MechR MechR+1;
/*************************************************************************************************
/* Startup of ElectRev

/ The following two criteria require that at least one drawing be available for review and that a
/ electrical design reviewer is available.

/ ENOUGH              ElectDS 'DrawingTable.Type1.Count>=1';

ENOUGH                ElectDS 'DrawingTable.ElectRevF.Count>=1';

DRAWWHERE             ElectDS 'ElectR==0&DrawingAtFront';

ONDRAW ElectDS ASSIGN ElectTime SimTime;

ENOUGH                        EP1 'ElectPer.CurCount>=1';

/ This criteria will only draw a project if it hasn't been reviewed by a electrical design reviewer

/ This step lists the duration of the electrical review which will be a normal distribution.


DURATION              ElectRev
'Normal[ElectRev.DrawingSet.ElectMu,ElectRev.DrawingSet.ElectSD]';
/*************************************************************************************************
/* Termination of ElectRev

ONRELEASE ElectDSRet ASSIGN ElectR ElectR+1;
/*************************************************************************************************
/* Startup of FLSRev

/ The following two criteria require that at least one drawing be available for review and that a
/ fire, life, and safety design reviewer is available.

/ ENOUGH              FLSDS 'DrawingTable.Type1.Count >=1';

ENOUGH                FLSDS 'DrawingTable.FLSRevF.Count>=1';

DRAWWHERE             FLSDS 'FLSR==0&DrawingAtFront';

/ ONDRAW FLSDS PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONDRAW FLSDS PRINT StdOutput "\tin FLSRev at\t%5.1f\n" SimTime;

ONDRAW FLSDS ASSIGN FLSTime SimTime;

ENOUGH                        FP1 'FLSPer.CurCount >= 1';

/ This criteria will only draw a project if it hasn't been reviewed by a fire, life, and safety
```

```
/ design reviewer

/ This step lists the duration of the fire, life, and safety review which will be a normal
/ distribution.

DURATION                FLSRev
'Normal[FLSRev.DrawingSet.FLSMu,FLSRev.DrawingSet.FLSSD]';
/***************************************************************************************************
/* Termination of FLSRev

ONRELEASE FLSDSRet ASSIGN FLSR FLSR+1;
/***************************************************************************************************
/* Startup of Review

ENOUGH RD1 'DrawingTable.ReworkF.Count>=1';

DRAWWHERE RD1 'ArchR==1&StructR==1&MechR==1&ElectR==1&FLSR==1';

ONDRAW RD1 ReworkFactor 1;

ONDRAW RD1 Reworked 0;

DURATION Review '0';
/***************************************************************************************************
/* Termination of Review
/***************************************************************************************************
/* Startup of Review1

DURATION Review1 '0';
/***************************************************************************************************
/* Termination of Review1

/* Rework factor, set to 1 if drawingset has never been repaired and to 2 if it has

STRENGTH RD4 'Review1.DrawingSet.r/Review1.DrawingSet.ReworkFactor';

STRENGTH RD3 100-Review1.DrawingSet.r/Review1.DrawingSet.ReworkFactor;
/***************************************************************************************************
/* Startup of OwnerRework

ENOUGH RD5 'Rework.ReworkF.Count>=1';

/ONFLOW RD3 PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONFLOW RD3 PRINT StdOutput "\tCOMPLETE at \t%5.1f\n" SimTime;

/ONFLOW RD3 PRINT StdOutput "\tReworked \t%5.0f \tTime(s)\t" Reworked;

ONFLOW RD3 ASSIGN CompleteTime SimTime;

/ONFLOW RD3 COLLECT PermitTime CompleteTime-ArchTime;
/ONFLOW RD3 COLLECT PermitTime CompleteTime-StructTime;
/ONFLOW RD3 COLLECT PermitTime CompleteTime-MechTime;
/ONFLOW RD3 COLLECT PermitTime CompleteTime-ElectTime;
/ONFLOW RD3 COLLECT PermitTime CompleteTime-FLSTime;
```

```
/ONFLOW RD3 PRINT StdOutput “Approval Time \t%5.1f\t,\t” PermitTime.MaxVal;

/ONFLOW RD3 PRINT StdOutput “Owner Rework Time \t%5.1f\n” OwnerReworkTotal;

/ ONFLOW RD3 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONFLOW RD3 PRINT StdOutput “\t(Arch) Comp Time \t%5.1f\n” CompleteTime-ArchTime;

/ ONFLOW RD3 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONFLOW RD3 PRINT StdOutput “\t(Struct) Comp Time \t%5.1f\n” CompleteTime-StructTime;

/ ONFLOW RD3 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONFLOW RD3 PRINT StdOutput “\t(Mech) Comp Time \t%5.1f\n” CompleteTime-MechTime;

/ ONFLOW RD3 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONFLOW RD3 PRINT StdOutput “\t(Elect) Comp Time \t%5.1f\n” CompleteTime-ElectTime;

/ ONFLOW RD3 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONFLOW RD3 PRINT StdOutput “\t(FLS) Comp Time \t%5.1f\n” CompleteTime-FLSTime;

ONDRAW RD5 ASSIGN OwnerStart SimTime;

ONDRAW RD5 ASSIGN RevError RevAssignError;

DURATION OwnerRework
‘Normal[OwnerRework.DrawingSet.ORewMu,OwnerRework.DrawingSet.ORewSD]’;

/Turn on these print statements to show the error assigned and the rework factor.

/ ONRELEASE RD6 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONRELEASE RD6 PRINT StdOutput “\tAssign Err No. \t%5.0f” RevError;

/ ONRELEASE RD6 PRINT StdOutput “\tRework Percent \t%5.1f\n” ‘r/ReworkFactor’;
/****************************************************************************************************
/* Termination of OwnerRework

ONRELEASE RD6 ASSIGN OwnerEnd SimTime;

ONRELEASE RD6 ASSIGN OwnerReworkTotal OwnerReworkTotal+(OwnerEnd-OwnerStart);

/ ONRELEASE RD6 PRINT StdOutput “Proj No. \t%5.1f” ResNum;

/ ONRELEASE RD6 PRINT StdOutput “\tOwner Rework Time \t%5.1f\n” OwnerReworkTotal;
/****************************************************************************************************
/* Startup of ReReviewA

PRIORITY ReReviewA ‘Resubmit.CurCount>0 ? 10 : 0’;

ENOUGH RDA ‘Resubmit.ReworkRevFA.Count>=1’;

DRAWWHERE RDA ‘RevError==100’;
```

```
/Turn on the print statement to check the reviewer assigned

/ ONDRAW RRA PRINT StdOutput "\t\t\t\t\tReview assign \t%5.0f\n" Type;

DURATION ReReviewA 'Normal
[ReReviewA.DrawingSet.RRevAMu,ReReviewA.DrawingSet.RRevASD]';
/*********************************************************************************************************
/* Termination of ReReviewA

ONRELEASE RDARet ASSIGN Reworked Reworked+1;

ONRELEASE RDARet ASSIGN ReworkFactor ReworkFactor+1;

ONRELEASE RDARet ASSIGN RevError 0;

/ ONRELEASE RDARet PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONRELEASE RDARet PRINT StdOutput "\tREWORKED \t\t%5.1f \tTime(s)\n" Reworked;
/*********************************************************************************************************
/* Startup of ReReviewS

PRIORITY ReReviewS 'Resubmit.CurCount>0 ? 10 : 0';

ENOUGH RDS 'Resubmit.ReworkRevFS.Count>=1';

DRAWWHERE RDS 'RevError==200';

/Turn on the print statement to check the reviewer assigned

/ ONDRAW RRS PRINT StdOutput "\t\t\t\t\tReview assign \t%5.0f\n" Type;

DURATION ReReviewS 'Normal
[ReReviewS.DrawingSet.RRevSMu,ReReviewS.DrawingSet.RRevSSD]';
/*********************************************************************************************************
/* Termination of ReReviewS

ONRELEASE RDSRet ASSIGN Reworked Reworked+1;

ONRELEASE RDSRet ASSIGN ReworkFactor ReworkFactor+1;

ONRELEASE RDSRet ASSIGN RevError 0;

/ ONRELEASE RDSRet PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONRELEASE RDSRet PRINT StdOutput "\tREWORKED \t\t%5.1f \tTime(s)\n" Reworked;
/*********************************************************************************************************
/* Startup of ReReviewM

PRIORITY ReReviewM 'Resubmit.CurCount>0 ? 10 : 0';

ENOUGH RDM 'Resubmit.ReworkRevFM.Count>=1';

DRAWWHERE RDM 'RevError==300';

/Turn on the print statement to check the reviewer assigned
```

```
/ ONDRAW RRM PRINT StdOutput "\t\t\t\t\tReview assign \t%5.0f\n" Type;

DURATION ReReviewM 'Normal
[ReReviewM.DrawingSet.RRevMMu,ReReviewM.DrawingSet.RRevMSD]';
/*****************************************************************************************************
/* Termination of ReReviewM

ONRELEASE RDMRet ASSIGN Reworked Reworked+1;

ONRELEASE RDMRet ASSIGN ReworkFactor ReworkFactor+1;

ONRELEASE RDMRet ASSIGN RevError 0;

/ ONRELEASE RDMRet PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONRELEASE RDMRet PRINT StdOutput "\tREWORKED \t\t%5.1f \tTime(s)\n" Reworked;
/*****************************************************************************************************
/* Startup of ReReviewE

PRIORITY ReReviewE 'Resubmit.CurCount>0 ? 10 : 0';

ENOUGH RDE 'Resubmit.ReworkRevFE.Count>=1';

DRAWWHERE RDE 'RevError==400';

/Turn on the print statement to check the reviewer assigned

/ ONDRAW RRE PRINT StdOutput "\t\t\t\t\tReview assign \t%5.0f\n" Type;

DURATION ReReviewE 'Normal
[ReReviewE.DrawingSet.RRevEMu,ReReviewE.DrawingSet.RRevESD]';
/*****************************************************************************************************
/* Termination of ReReviewE

ONRELEASE RDERet ASSIGN Reworked Reworked+1;

ONRELEASE RDERet ASSIGN ReworkFactor ReworkFactor+1;

ONRELEASE RDERet ASSIGN RevError 0;

/ ONRELEASE RDERet PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONRELEASE RDERet PRINT StdOutput "\tREWORKED \t\t%5.1f \tTime(s)\n" Reworked;
/*****************************************************************************************************
/* Startup of ReReviewF

PRIORITY ReReviewF 'Resubmit.CurCount>0 ? 10 : 0';

ENOUGH RDF 'Resubmit.ReworkRevFF.Count>=1';

DRAWWHERE RDF 'RevError==500';

/Turn on the print statement to check the reviewer assigned

/ ONDRAW RRF PRINT StdOutput "\t\t\t\t\tReview assign \t%5.0f\n" Type;
```

```
DURATION ReReviewF 'Normal
[ReReviewF.DrawingSet.RRevFMu,ReReviewF.DrawingSet.RRevFSD]';
/*************************************************************************************************
/* Termination of ReReviewF

ONRELEASE RDFRet ASSIGN Reworked Reworked+1;

ONRELEASE RDFRet ASSIGN RevError 0;

/ ONRELEASE RDFRet PRINT StdOutput "Proj No. \t%5.1f" ResNum;

/ ONRELEASE RDFRet PRINT StdOutput "\tREWORKED \t\t%5.1f \tTime(s)\n" Reworked;
/*************************************************************************************************
/* Startup of Report

ENOUGH R1
'Complete.ReworkF.Count==Type1proj+Type2proj+Type3proj+Type4proj+Type5proj';

/ ENOUGH R1 'Complete.ReworkF.Count==10';

DRAWWHERE R1 'DrawingAtFront1';

DRAWUNTIL R1
'Report.DrawingSet.Count==Type1proj+Type2proj+Type3proj+Type4proj+Type5proj' ;

DURATION Report 0;

ONRELEASE R2 COLLECT PermitTime CompleteTime-ArchTime;
ONRELEASE R2 COLLECT PermitTime CompleteTime-StructTime;
ONRELEASE R2 COLLECT PermitTime CompleteTime-MechTime;
ONRELEASE R2 COLLECT PermitTime CompleteTime-ElectTime;
ONRELEASE R2 COLLECT PermitTime CompleteTime-FLSTime;

ONRELEASE R2 PRINT StdOutput "Proj No.\t%4.0f" ResNum;

ONRELEASE R2 PRINT StdOutput "\tReworked\t%2.0f\tTime(s)\t" Reworked;

ONRELEASE R2 PRINT StdOutput "Approval Time\t%5.1f\t,\t" PermitTime.MaxVal;

ONRELEASE R2 PRINT StdOutput "Owner Rework Time\t%5.1f\t,\n" OwnerReworkTotal;
/*************************************************************************************************
/* Termination of Report
/*************************************************************************************************
/* Entry of resources into OArchPer

INIT OArchPer 10;
/*************************************************************************************************
/* Initialization of Queues, Running the Simulation, Presenting Results

SIMULATEUNTIL 'Complete1.Type1.Count==Type1proj&Complete1.Type2.Count==Type2proj&

        Complete1.Type3.Count==Type3proj&Complete1.Type4.Count==Type4proj&
                              Complete1.Type5.Count==Type5proj';
```

# Appendix D Validation Output Information

I present the following output as a way to validate the computer model presented in chapter 6. Figure D-1 shows projects entering the system according to when they were defined in the computer code.

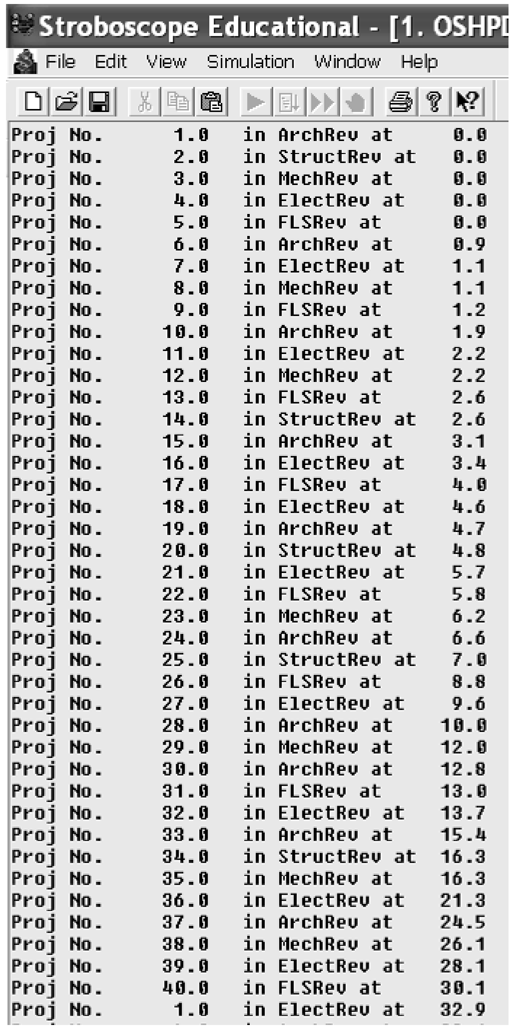



Figure D-1 Loading System, No Sorting Key

Figure D-1 shows the project number and when it was taken into the respective reviewer. For example project 1 is taken in to the architect for review first, project 2 is taken into the structural engineer for review second, and so on in descending order.

This is not a realistic way of how the organization receives and reviews drawings. For example a category III project will come in before a category II or category I project and will be worked on in that order. The organization typically structures their work in a first in first out order.

To simulate a first in first out review situation, the discrete event simulation model generates a random number and assigns it to each of the projects when they initially enter the system. The projects are ordered according to their random number. The following code generates this randomization which reorders how the projects are reviewed.

*VARIABLE RandomNumber 'Rnd[]';*

*SAVEPROPS DrawingSet RandomNo;*

*VARPROP DrawingSet DiscipProp RandomNo;*

Filters ensure that the drawing at front is reviewed first by the available reviewer.

*FILTER DrawingAtFront DrawingSet 'RandomNo==DrawingTable.RandomNo.MinVal';*

*DISCIPLINE DrawingTable DiscipProp;* The discipline of the queue DrawingTable is set to follow the order in which the drawings were ranked in accordance with the random number.

*ONDRAW DS1 ASSIGN RandomNo RandomNumber;* This "ondraw" code generates a random number for each of the projects and assigns it to a saved property.

*DRAWWHERE ArchDS 'ArchR==0&DrawingAtFront';* This "drawwhere" code draws a project into the architect for review which has not been reviewed yet and meets the criteria of the random number order.

Figure D-2 shows the projects with a random number assigned and how they are taken in by the simulation model.

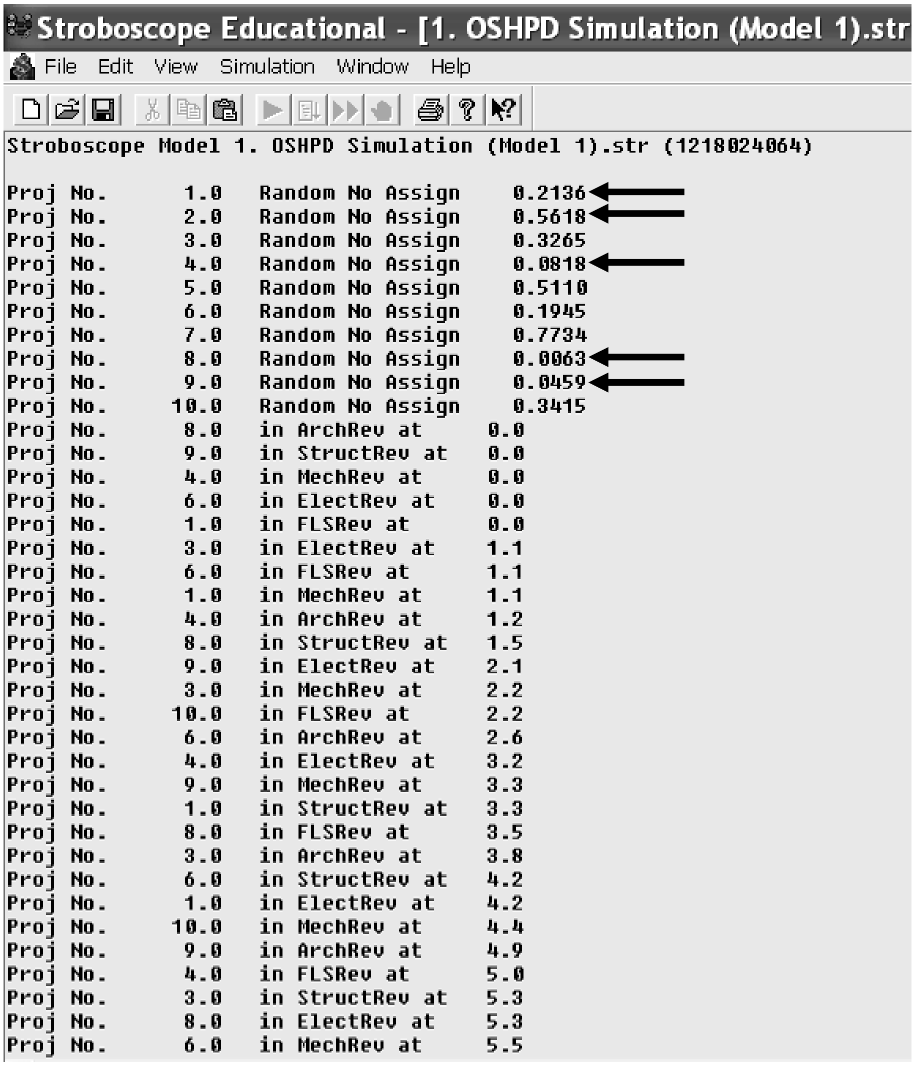



Figure D-2 Loading System With a Sorting Key Random

Figure D-2 shows the project number and the resultant random number generated.

Project number 1 is assigned 0.2136, project number 2 is assigned 0.5618.

*FILTER DrawingAtFront DrawingSet 'RandomNo==DrawingTable.RandomNo.MinVal';*

The "filter" code then reorders the projects to have the minimum value to enter the review first, which in this situation is project number 8 which is assigned a number

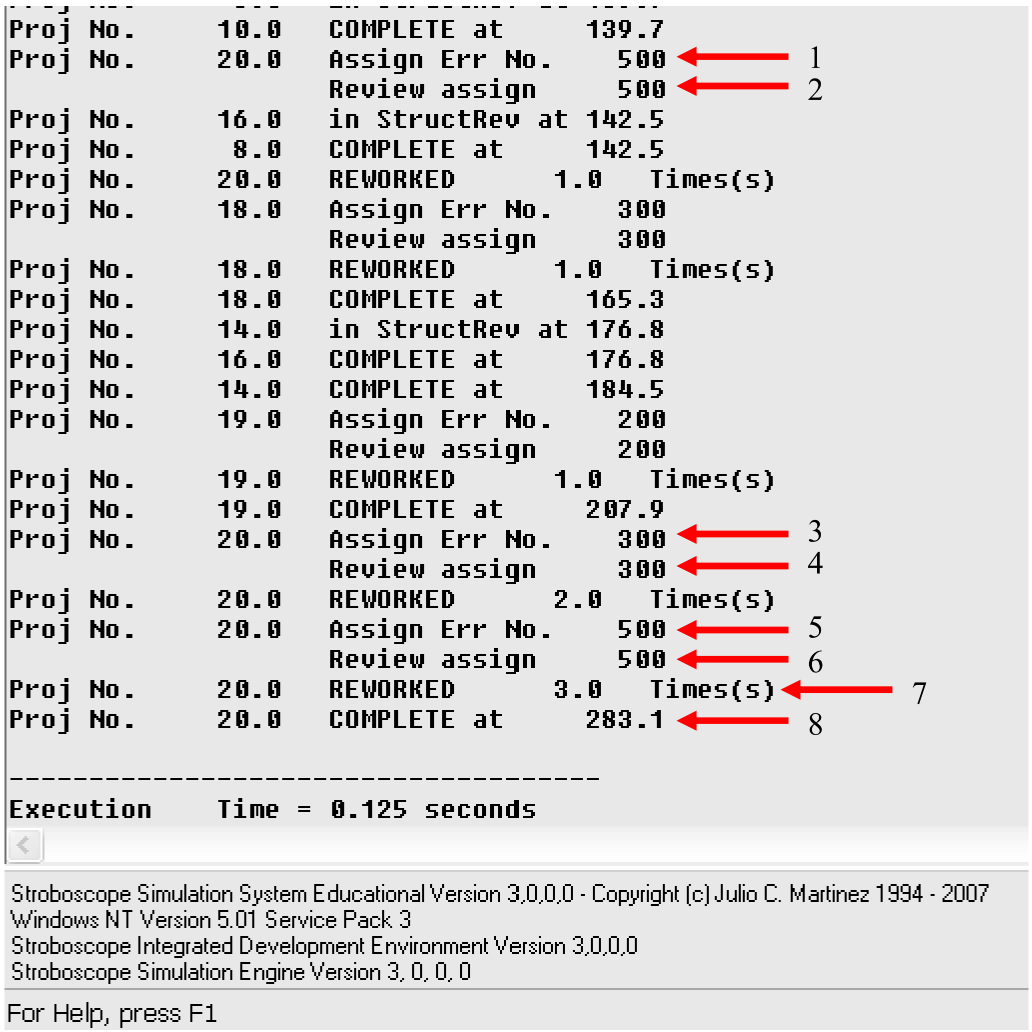
0.0063, then project number 9 with a random number of 0.0459, then project number 4 with a random number of 0.0818 and so on until all the projects are reviewed.

The rework percentage is dependent on the rework cycle. Figure D-3 illustrates a changing rework percentage. It shows that if a rework percentage is assigned to 100%, then on the second rework cycle, the rework percentage will be 50% as shown by arrows 6 and 7.

```
Proj No.      2.0   in StructRev at    7.6
Proj No.      3.0   Assign Err No.     300   Rework Percent   100.0   1
                    Review assign      300
Proj No.      4.0   Assign Err No.     200   Rework Percent   100.0   2
                    Review assign      200
Proj No.      5.0   Assign Err No.     100   Rework Percent   100.0   3
                    Review assign      100
Proj No.      1.0   Assign Err No.     500   Rework Percent   100.0   4
                    Review assign      500
Proj No.      3.0   REWORKED       1.0   Time(s)
Proj No.      4.0   REWORKED       1.0   Time(s)
Proj No.      4.0   COMPLETE at       23.6
Proj No.      5.0   REWORKED       1.0   Time(s)
Proj No.      2.0   Assign Err No.     100   Rework Percent   100.0   5
                    Review assign      100
Proj No.      1.0   REWORKED       1.0   Time(s)
Proj No.      1.0   COMPLETE at       24.5
Proj No.      2.0   REWORKED       1.0   Time(s)
Proj No.      2.0   COMPLETE at       25.2
Proj No.      3.0   Assign Err No.     400   Rework Percent    50.0   6
                    Review assign      400
Proj No.      5.0   Assign Err No.     300   Rework Percent    50.0   7
                    Review assign      300
Proj No.      3.0   REWORKED       2.0   Time(s)
Proj No.      3.0   COMPLETE at       39.4
Proj No.      5.0   REWORKED       2.0   Time(s)
```

Figure D-3 Dynamic Rework

Figure D-4 illustrates how a project can be reworked multiple times with different types of errors assigned. In this example project 20 is highlighted with arrow 1. It entered the rework process and was assigned the error 500 which means it was a fire, life, and safety error. It was then assigned the fire, life, and safety reviewer as highlighted by arrow 2. It was then determined to require another rework cycle as shown by arrows 3 and 4 with an assigned error of 300 which represents a mechanical issue. Finally it was then required to be reworked again by being assigned an error of 500 or the fire, life, and safety discipline. The project was finally completed after being reworked three times as noted by arrow 7 and completed at time 283.1 days as marked by arrow 8.



```
Proj No.     10.0   COMPLETE at     139.7
Proj No.     20.0   Assign Err No.    500   1
                    Review assign     500   2
Proj No.     16.0   in StructRev at 142.5
Proj No.      8.0   COMPLETE at     142.5
Proj No.     20.0   REWORKED       1.0   Times(s)
Proj No.     18.0   Assign Err No.    300
                    Review assign     300
Proj No.     18.0   REWORKED       1.0   Times(s)
Proj No.     18.0   COMPLETE at     165.3
Proj No.     14.0   in StructRev at 176.8
Proj No.     16.0   COMPLETE at     176.8
Proj No.     14.0   COMPLETE at     184.5
Proj No.     19.0   Assign Err No.    200
                    Review assign     200
Proj No.     19.0   REWORKED       1.0   Times(s)
Proj No.     19.0   COMPLETE at     207.9
Proj No.     20.0   Assign Err No.    300   3
                    Review assign     300   4
Proj No.     20.0   REWORKED       2.0   Times(s)
Proj No.     20.0   Assign Err No.    500   5
                    Review assign     500   6
Proj No.     20.0   REWORKED       3.0   Times(s)   7
Proj No.     20.0   COMPLETE at     283.1   8

--------------------------------------
Execution     Time = 0.125 seconds

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Windows NT Version 5.01 Service Pack 3
Stroboscope Integrated Development Environment Version 3,0,0,0
Stroboscope Simulation Engine Version 3, 0, 0, 0
For Help, press F1
```
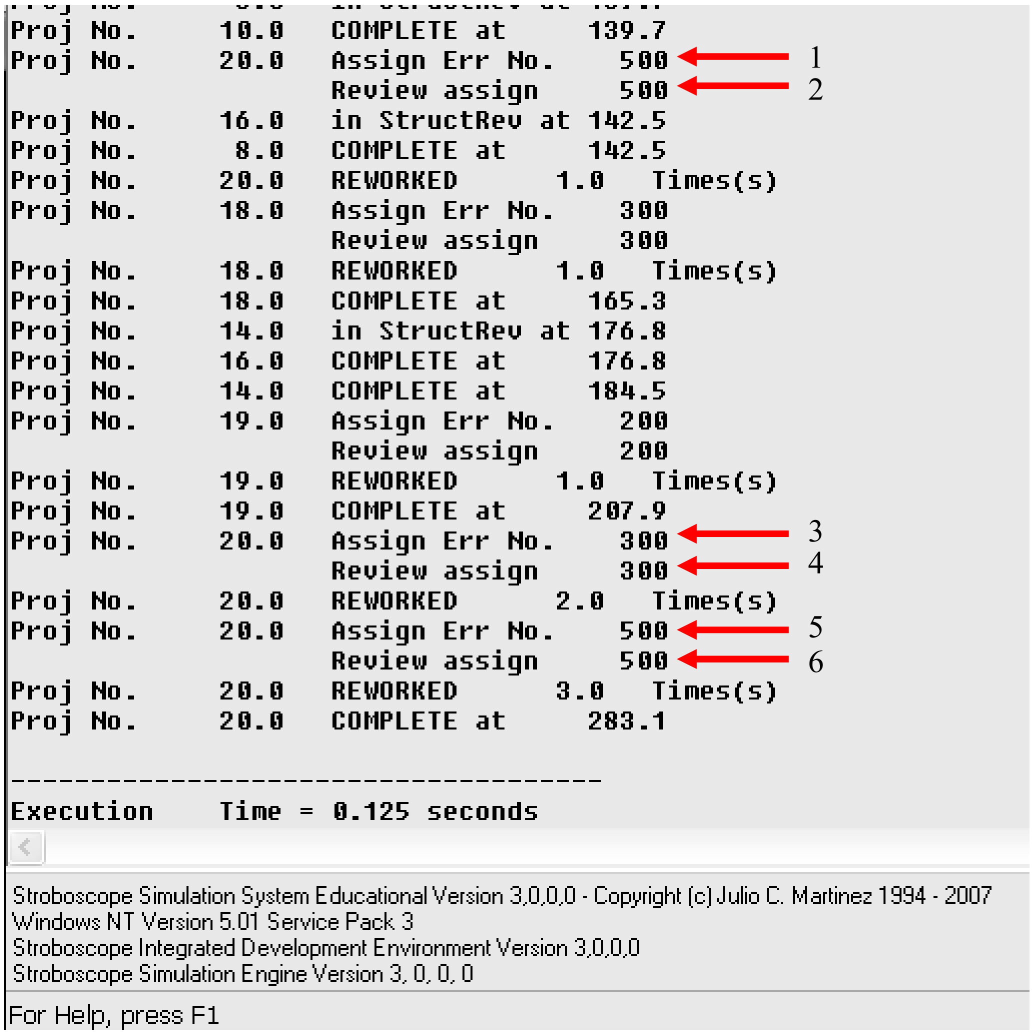

Figure D-4 Example of Multiple Rework Cycles

Figure D-5 shows output from the model that highlights the matching issue. Arrows 1, 3 and 5 show the error that is assigned. Arrows 2, 4, and 6 show that the reviewer assigned to correct the error matches the assigned error number.



```
Proj No.     10.0   COMPLETE at      139.7
Proj No.     20.0   Assign Err No.    500    1
                    Review assign     500    2
Proj No.     16.0   in StructRev at 142.5
Proj No.      8.0   COMPLETE at      142.5
Proj No.     20.0   REWORKED       1.0   Times(s)
Proj No.     18.0   Assign Err No.    300
                    Review assign     300
Proj No.     18.0   REWORKED       1.0   Times(s)
Proj No.     18.0   COMPLETE at      165.3
Proj No.     14.0   in StructRev at 176.8
Proj No.     16.0   COMPLETE at      176.8
Proj No.     14.0   COMPLETE at      184.5
Proj No.     19.0   Assign Err No.    200
                    Review assign     200
Proj No.     19.0   REWORKED       1.0   Times(s)
Proj No.     19.0   COMPLETE at      207.9
Proj No.     20.0   Assign Err No.    300    3
                    Review assign     300    4
Proj No.     20.0   REWORKED       2.0   Times(s)
Proj No.     20.0   Assign Err No.    500    5
                    Review assign     500    6
Proj No.     20.0   REWORKED       3.0   Times(s)
Proj No.     20.0   COMPLETE at      283.1

--------------------------------------
Execution    Time = 0.125 seconds
```

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Windows NT Version 5.01 Service Pack 3
Stroboscope Integrated Development Environment Version 3,0,0,0
Stroboscope Simulation Engine Version 3, 0, 0, 0

For Help, press F1

Figure D-5 Error Assignment

Assigning Rework is accomplished through a random number generator.

*VARIABLE RevAssignError* *'Rnd[] <= 1/5 ? 100:*

*LastRnd[] <= 2/5 ? 200:*

*LastRnd[] <= 3/5 ? 300:*

*LastRnd[] <= 4/5 ? 400: 500';*

This code assigns RevAssignError by generating a random number and then assigning it to either 100, 200, 300, 400, or 500. Those respective numbers represent either the architect, structural, mechanical, electrical or fire, life, and safety. The code below shows how the characterized resources of the review person are identified by type.

```
CHARTYPE    ReviewPer                           Type; /RP
/==========================================================
SUBTYPE         ReviewPer       Arch        100;
SUBTYPE         ReviewPer       Struct      200;
SUBTYPE         ReviewPer       Mech        300;
SUBTYPE         ReviewPer       Elect       400;
SUBTYPE         ReviewPer       FLS         500;
/--------------------------------------------------
```

Upon determination if the drawings require rework, when the projects are drawn into OwnerRework a random number is assigned to the project and the required reviewer is determined. This is shown by the code below.

*ONDRAW RD5 ASSIGN RevError RevAssignError;*

This property is carried with the project and upon completion of OwnerRework the ReReview process occurs. For example, if the error is assigned an architect error it will then be routed into the Architect ReReview combi using the following code.

*DRAWWHERE RDA 'RevError==100';*

This "drawwhere" code ensures that the project which is assigned an architect error is re-reviewed by the architect activity.

Once the project is re-reviewed by the architect the random number assigned is reset to zero.

*ONRELEASE RDARet ASSIGN RevError 0;*

This reset occurs because the project then goes back to rework decision to determine if the project requires another round of rework. If rework is not needed, the project flows into the complete queue. If it requires rework then the project is reassigned a random number and a discipline error is assigned. The process continues until that project requires no more rework and enters the complete queue. The model output tracks the number of times the project is reworked and becomes vital information in determining the overall time to permit the drawings.

Similar statements mirror this error assignment for structural, mechanical, electrical and fire, life, and safety. The code fragments are shown below.

Structural - *DRAWWHERE RDS 'RevError==200';*

*ONRELEASE RDSRet ASSIGN RevError 0;*

Mechanical -*DRAWWHERE RDM 'RevError==300';*

*ONRELEASE RDMRet ASSIGN RevError 0;*

Electrical - *DRAWWHERE RDE 'RevError==400';*

*ONRELEASE RDERet ASSIGN RevError 0;*

Fire, life, and safety - *DRAWWHERE RDF 'RevError==500';*

*ONRELEASE RDFRet ASSIGN RevError 0;*

# Appendix E Resampling Code for Case II

Following is code generated to run the resampling analysis program. The lines of code that begins with the # symbol are comments in the program and do not impact the computer program.

```
# Code to plot histograms from data collected

Line 1: sample = c(45,8,2,51,3,16,8,25,29,15,4,20,1,54,1,42,29,2,29,67,
52,1,36,1,1,1,1,2,1,1)

# Create a vector in which to store type3 values
Line 2: Value=numeric(1000)

Line 3: n=length(sample)

# Setup a loop to generate the 1000 values
Line 4: Value = sapply(1:1000, function(x) {mean(sample (type3, n,
replace=T))})

Line 5: hist(Value)

Line 6: print (hist (Value))

Line 7: print (mean (Value))

Line 8: print (sd (Value))
```

Line 1 creates a vector of numbers that were calculated from a spreadsheet.

Line 2 creates another vector that will hold 1000 vectors of the same length as the original vector. In this case, the original vector contains 30 values.

Line 3 requires each generated vector to have the same amount of data points as the original vector which for all resampling code is 30.

Line 4 generates a loop that takes the mean of each of the generated vectors and then stores them in the Value vector.

Line 5 creates a histogram of the Value vector.

Lines 6 through 8 print the histogram, mean of the 1000 values and standard deviation of the 1000 values.

Figure E-1 shows a sample output from this resampling code.

```
RGui
File  Edit  View  Misc  Packages  Windows  Help
R Console
Type 'demo()' for some demos, 'help()' for on-line help, or
'help.start()' for an HTML browser interface to help.
Type 'q()' to quit R.

> source("C:\\Program Files\\R\\R-2.5.1\\2. Mean and SD\\4. 10Mto50M (Elect)")
$breaks
 [1]  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17

$counts
 [1]   2  33  77 143 222 203 140  93  57  22   5   1   1   1

$intensities
 [1] 0.002000000 0.033000000 0.077000000 0.143000000 0.222000000 0.203000000
 [7] 0.140000000 0.093000000 0.057000000 0.022000000 0.005000000 0.001000000
[13] 0.001000000 0.001000000

$density
 [1] 0.002000000 0.033000000 0.077000000 0.143000000 0.222000000 0.203000000
 [7] 0.140000000 0.093000000 0.057000000 0.022000000 0.005000000 0.001000000
[13] 0.001000000 0.001000000

$mids
 [1]  3.5  4.5  5.5  6.5  7.5  8.5  9.5 10.5 11.5 12.5 13.5 14.5 15.5 16.5

$xname
[1] "Value"

$equidist
[1] TRUE

attr(,"class")
[1] "histogram"
[1] 8.2582
[1] 1.891769
>
```

Figure E-1 Sample Output from Resampling Code

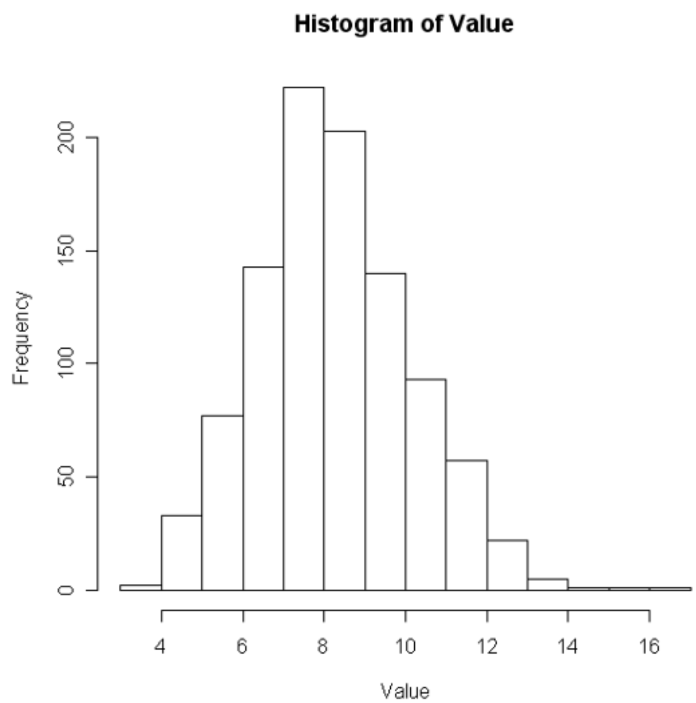


Figure E-2 Sample Histogram

As shown in figure E-1 the mean was calculated to be 8.26 and the standard deviation 1.89 for the 1000 values stored in the Value vector. The histogram (figure E-2) shows the review times resemble a normal curve.

Following is code used to calculate the review times for each review discipline and for each project category.

## Category I (Less than $50K)

### Architectural Review (Less than $50K)

```
# Code to plot histograms from data collected

type3 = c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,6)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

### Electrical Review (Less than $50K)

```
# Code to plot histograms from data collected

type3 = c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Fire, Life, and Safety Review (Less than $50K)

```
# Code to plot histograms from data collected

type3 = c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2,3,2,7)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Mechanical Review (Less than $50K)

```
# Code to plot histograms from data collected

type3 = c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Structural Review (Less than $50K)

```
# Code to plot histograms from data collected

type3 = c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,5,7,8,8)

#Create a vector in which to store type3 values
Value=numeric(1000)
```

```
# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

## Category II (Greater than $50K and less than or equal to $1M)

Architectural Review (Greater than $50K and less than or equal to $1M)

```
# Code to plot histograms from data collected

# Code to plot histograms from data collected

type3 =
c(1,7,2,2,1,5,1,3,1,1,1,1,1,1,1,1,7,1,1,1,3,1,1,1,1,1,2,1,1,1,1,1,1,1,1
)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Electrical Review (Greater than $50K and less than or equal to $1M)

```
# Code to plot histograms from data collected

type3 = c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2,2,2,2)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)
```

```
Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Fire, Life, and Safety Review (Greater than $50K and less than or equal to $1M)

```
# Code to plot histograms from data collected

type3 = c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2,2,3,7)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Mechanical Review (Greater than $50K and less than or equal to $1M)

```
# Code to plot histograms from data collected

type3 = c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,2,2,2,2,2,2,4,14,60)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Structural Review (Greater than $50K and less than or equal to $1M)

```
# Code to plot histograms from data collected

type3 = c(1,1,2,2,2,1,1,1,3,4,4,6,3,1,2,2,3,1,3,3,1,1,2,1,4,1,3,12,4,2)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

## Category III (Greater than $1M and less than or equal to $10M)

Architectural Review (Greater than $1M and less than or equal to $10M)

```
# Code to plot histograms from data collected

type3 =
c(2,1,1,1,1,1,1,1,1,9,1,4,3,1,3,4,11,1,1,1,1,1,1,1,3,1,6,4,1,18)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Electrical Review (Greater than $1M and less than or equal to $10M)

```
# Code to plot histograms from data collected
```

```
type3 =
c(1,1,1,1,5,28,1,6,1,27,3,1,3,1,1,13,1,1,1,4,2,2,3,8,1,1,3,1,7,2)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Fire, Life, and Safety Review (Greater than $1M and less than or equal to $10M)

```
# Code to plot histograms from data collected

type3 =
c(1,18,1,1,6,8,1,6,6,1,1,1,2,9,9,1,8,1,1,1,3,2,2,1,13,1,2,1,5,8)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Mechanical Review (Greater than $1M and less than or equal to $10M)

```
# Code to plot histograms from data collected

type3 =
c(2,11,1,2,5,8,1,6,2,20,2,1,6,2,3,1,6,1,6,2,15,2,3,2,1,8,2,6,2,2)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)
```

```
Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Structural Review (Greater than $1M and less than or equal to $10M)

```
# Code to plot histograms from data collected

type3 =
c(11,15,1,3,10,8,2,2,2,16,24,20,8,19,7,16,10,5,2,3,4,8,3,12,8,6,1,9,7,8
)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

## Category IV (Greater than $10M)

Architectural Review (Greater than $10M)

```
# Code to plot histograms from data collected

type3 =
c(17,3,3,1,1,2,1,24,3,1,16,2,5,1,4,1,11,1,11,8,38,15,16,9,18,1,36,1,1,1
)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
```

```
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Electrical Review (Greater than $10M)

```
# Code to plot histograms from data collected

type3 =
c(7,8,4,1,4,3,24,10,1,7,7,10,4,43,1,44,9,8,1,15,2,14,9,1,1,1,1,2,1,5)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Fire, Life, and Safety Review (Greater than $10M)

```
# Code to plot histograms from data collected

type3 =
c(45,8,2,51,3,16,8,25,29,15,4,20,1,54,1,42,29,2,29,67,52,1,36,1,1,1,1,2
,1,1)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))
```

```
print (sd (Value))
```

Mechanical Review (Greater than $10M)

```
# Code to plot histograms from data collected

type3 =
c(16,1,1,43,2,15,9,2,15,1,5,12,7,9,16,2,3,55,2,15,1,17,22,1,42,1,6,4,1,
1)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```

Structural Review (Greater than $10M)

```
# Code to plot histograms from data collected

type3 =
c(67,166,28,8,21,6,55,5,4,63,1,15,2,4,1,1,2,59,1,6,29,9,16,28,7,15,4,11
,3,4)

#Create a vector in which to store type3 values
Value=numeric(1000)

# Setup a loop to generate the 1000 values
n=length(type3)

Value = sapply(1:1000, function(x) {
 mean(sample (type3, n, replace=T))
})
hist(Value)

print (hist (Value))

print (mean (Value))

print (sd (Value))
```