# Use of Work Structuring to Increase Performance of Project-Based Production Systems

by

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# Abstract

## Use of Work Structuring to Increase Performance of Project-Based Production Systems

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Work Structuring is a fundamental form of planning. It determines *what* work must be done on a project, *who* would be best-suited to execute it, and *when* they should be doing it. This dissertation seeks to apply a framework for studying Work Structuring. Although the Work Structuring concept is not new – practitioners have been "structuring work" for as long as construction projects have existed – we need a formal framework so that practitioners and researchers will have a common language for structuring practice, research, and teaching. We used case studies to examine Work Structuring because case studies help us understand phenomena and facilitate theory building. We intentionally structured our case studies to focus on different project phases and systems to demonstrate the applicability of the Work Structuring concept.

Our first case study, the Hollow Metal Door Frames case study (i.e., "Case 1") discusses how project participants failed to adopt a systems-oriented perspective,

working instead within a purchasing mentality. Case 1 investigates standard practice and helps formulate an initial framework for Work Structuring research.

Our second case study, the Steel Indirect Light Fixtures case study (i.e., “Case 2”) explains how efforts in product development and supply chain management allowed the fabricator to introduce a competitive new product for lighting delivery. Case 2 highlights effective Work Structuring practice and provides feedback on the initial framework.

Our third case study, the Stone on Truss Curtain Wall case study (i.e., “Case 3”) investigates missed opportunities for global optimization during design collaboration meetings. Case 3 presents a methodology to help project participants manage the relationship between design and production and experiments with methods to make Work Structuring issues transparent.

Through our case studies, we clarified and experimented with the Work Structuring concept and highlighted how Work Structuring might be used to reveal additional opportunities for value generation. Our case studies provided insight into Work Structuring practice, and we identified methods to overcome the constraints of contracts, trade regulations, and traditional work methods. Thus, the framework we applied provides the AEC industry with a new way of managing the relationship between design, fabrication, and installation.

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*The real voyage of discovery consists not in seeking new landscapes*
*but in having new eyes.*

Marcel Proust

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*To my mom, Theresa Yoh-Yun Ko.*

# CHAPTER 1 – INTRODUCTION

## 1.1 – Introduction

Architecture-Engineering-Construction (AEC) project participants recognize the importance of product and process design integration in improving overall project execution. This is evident through the increasing use of, for example: (1) design-build contracting in both the public and private sectors, (2) partnering as a means to negotiate conflicts between designers and builders, and (3) constructability and value engineering to prevent or resolve process design problems by adjusting the product design. Project participants combine personal knowledge and experience, standard company practice, and anecdotes from colleagues to guide the way in which they approach product and process design integration. They may also attend professional meetings and trade conferences, and consult related literature to gain further insight into collaborative practices and emerging technologies that facilitate design integration.

Some barriers stand in the way of the effectiveness of this approach: (1) it relies on the initiative and ability of project participants to pull from a wealth of knowledge or experience, (2) project participants may hesitate to make a recommendation that improves overall project performance, especially if it adversely impacts their own work, and (3) an owner’s contracting approach may limit funds during the early stages of project development, so project participants lack the resources needed to develop a range of innovative alternative product and process designs. To overcome such barriers, the

AEC industry needs a formal framework consisting of organizing principles and techniques to guide efforts in product and process design integration.

## 1.2 – Concepts and Terminology

Ballard (1999) introduced the concept of Work Structuring as a foundation for a formal framework for product and process design integration. By clarifying related concepts and terminology, we align the framework for use across different case studies. Then, with the consistency of a common language, we can begin building and understanding the theoretical underpinnings of Work Structuring.

### 1.2.1 – Work Structuring

The Lean Construction Institute (LCI) initially equated the term ‘Work Structuring’ with process design (Ballard 1999). Ballard (2000b) then adjusted the term ‘Work Structuring’ to represent “the most fundamental level of process design,” specifically:

- **Work Structuring –** “The development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts” with the goal of making “work flow more reliable and quick while delivering value to the customer” (Ballard 2000b).

Ballard et al. (2001) later expanded Work Structuring to encompass ‘production system design.’ Work Structuring can also be described as a fundamental skill based on organizing principles (Tsao et al. 2004), and its output becomes a Work Structure.

- **Work Structure** – The description of “how work on a project will create a product that meets customer needs” (Tsao et al. 2004).

Jin et al. (1999) and Zhao and Jin (2003) also investigated the role of Work Structures in the collaborative process, albeit with an emphasis in mechanical engineering design.

Ballard and Howell (2003) used the term ‘Work Structuring’ instead of ‘Process Design’ because they “wanted to critique the prevailing practice of work breakdown structures.” They argued that “planning must be done across work scopes, and not only for work scopes in isolation.” Otherwise, “unachievable schedule goals are often established and the coordination of interdependent activities is left to the workers.”

Work Structuring is a major aspect of the Lean Project Delivery System (LPDS).

- **Lean Project Delivery System (LPDS)** – A production management-based approach to designing and building capital facilities in which “the project is structured and managed as a value generating process” (Ballard 2000b).

The LPDS “will be developed as a philosophy, a set of interdependent functions, rules for decision making, procedures for execution of functions, and as implementation aids and tools,” and its domain encompasses ‘project-based production systems,’ i.e., “where projects and production systems intersect” (Ballard 2000b).

- **Project-based Production System –** A temporary infrastructure of resources and value-generating processes strategically arranged for new product or capital facility development.

The LPDS model consists of modules organized into overlapping triads representing five different project phases (Ballard 2003) (Figure 1). Each phase, as represented by a triangle, consists of essential steps that lead to project completion.

Work Structuring occurs throughout the project as project participants define and redefine plans that describe the type of work required for a project. As Work Structuring establishes the plan, Production Control makes sure work is executed as planned.

- **Production Control –** The processes that "govern execution of plans and extend throughout a project" where "'control' means causing a desired future rather than identifying variances between plan and actual" (Ballard 2000b).

Production Control uses the lookahead process to manage work flow control and weekly work planning to manage production unit control (Ballard 2000b). Thus, Work Structuring and Production Control are complementary and managed concurrently during all phases of project delivery.

Typically, during the Project Definition and Lean Design phases, planners develop and compare various Work Structures to determine an appropriate one for use on the project. During the Lean Supply and Lean Assembly phases, project participants begin executing the selected Work Structure. If they find they cannot execute certain aspects of the selected Work Structure, they may modify it to better match their capabilities. Thus, Work Structuring is an ongoing, adaptive process. Finally, during the facility's Use phase, project participants determine if the executed Work Structure successfully met customer needs. They can then funnel their experience into a learning loop to guide Work Structuring efforts on future projects (Howell and Ballard 1999).

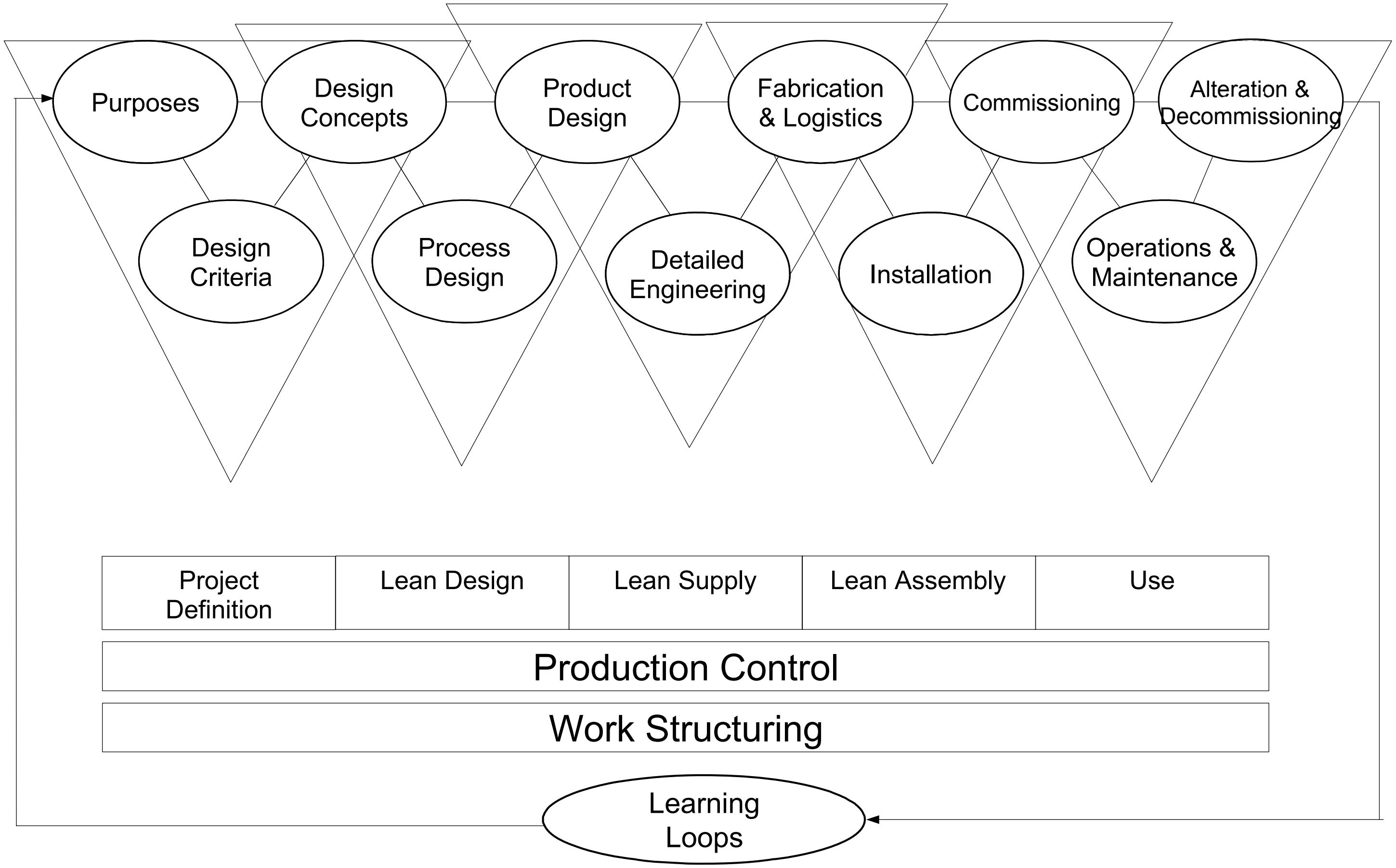

*Figure 1: Lean Project Delivery System (Ballard 2003)*

### 1.2.2 – Production Units, Work Chunks, and Handoffs

Ballard (1999) used the terms ‘production units,’ ‘work chunks,’ and ‘handoffs’ to describe facets of Work Structuring.

- **Production unit** – “a group of direct production workers that do or share responsibility for similar work, drawing on the same skills and techniques” (LCI 2004).

Ballard and Koskela (1998) initially defined a production unit as “an individual or a group responsible for a certain part of the work to be accomplished.” Accordingly, production units are recipients of work assignments. LCI introduced the phrase ‘production unit’ to provide a neutral term that describes a collection of any number of workers of any skill (e.g., design squads, construction crews, or any other work group).

- **Work chunk** – “A unit of work that can be handed off from one production unit to the next” (Tsao et al. 2000). As production units add value to a work chunk, it transforms with each production step until it becomes completed work. Specifically, a work chunk can be managed as “a unique combination of (1) an action (e.g., casting, assembling, or digging) to be performed on (2) a physical element (e.g., beams, columns, windows or pipes) [and] located in (3) a zone (e.g., a building, a level, an apartment, or a room)” (Marchesan and Formoso 2001) or as a process that combines (1) directives, (2) prerequisite work, and (3) resources to generate an output (LCI 2004).

- **Handoff –** The combined (1) completion of a work chunk by a production unit that allows a subsequent production unit to further transform the work chunk or execute a different work chunk as planned, (2) declaration of completion of the work chunk by the production unit and release to the subsequent production unit, and (3) acceptance of the released work by the subsequent production unit.

Handoffs directly impact the ability of production units to execute work chunks as planned. To illustrate this, Tommelein et al. (1999) demonstrate how it "is possible to reduce waste and shorten project duration by improving the reliability of work flow between trades."

Ballard and Howell (2003) proposed that "schedules are products of Work Structuring that specify goals and the handoffs between specialists required to achieve those goals. Production control has the job of achieving those handoffs or initiating replanning should that prove infeasible." Based on targets and milestones from the master project schedule, they recommend the development of reverse phase schedules which work "from a target completion date backwards, which causes tasks [i.e., work chunks] to be defined and sequenced so that their completion releases work; i.e., achieves a handoff." Thus, work chunks of any size are defined at the handoff level, from higher handoff levels that deal with phasing itself (e.g., "First Building A, then Building B,…") to lower handoff levels that deal with the operations performed within the processes that occur between higher level handoffs.

Furthermore, the definition of production units and handoffs can be interdependent. If handoffs are not executed as planned, production units might be restructured to handle future work. Such restructuring could result, for instance, in the development of composite crews with different skill sets or work groups taking on non-traditional tasks.

Figure 2 provides a conceptual representation of the relationship between a Work Structure, its work chunks, and handoffs between the work chunks. A Work Structure is made up of work chunks which vary in size and scope. Project planners assign production units to manage the execution of each work chunk. Handoffs link dependent work chunks and establish how work flows within a project.

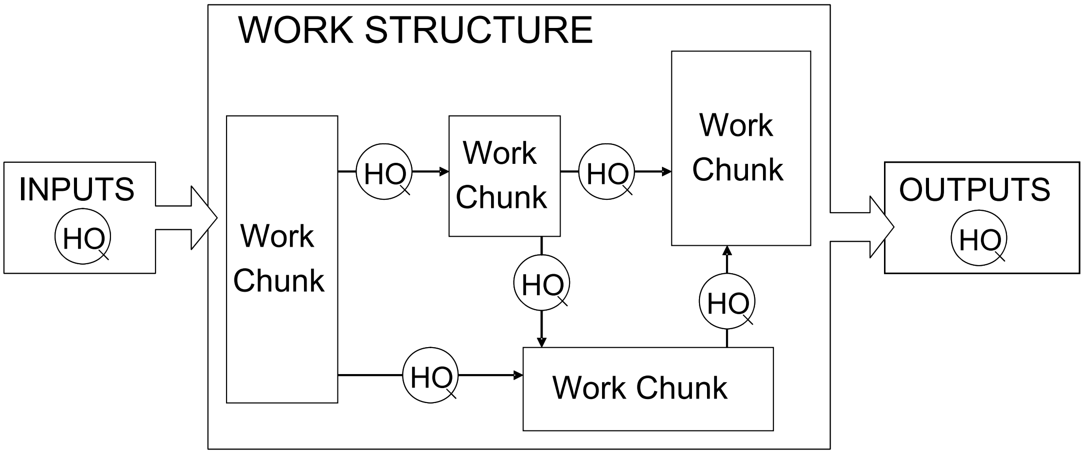

*Figure 2: Relationship between a Work Structure and its Work Chunks and Handoffs (“HO” = Handoff as a Resource Queue)*

As mentioned earlier, a work chunk can also be represented via activity definition model (ADM) as a process that combines (1) directives, (2) prerequisite work, and (3) resources to generate an output (LCI 2004) (Figure 3).

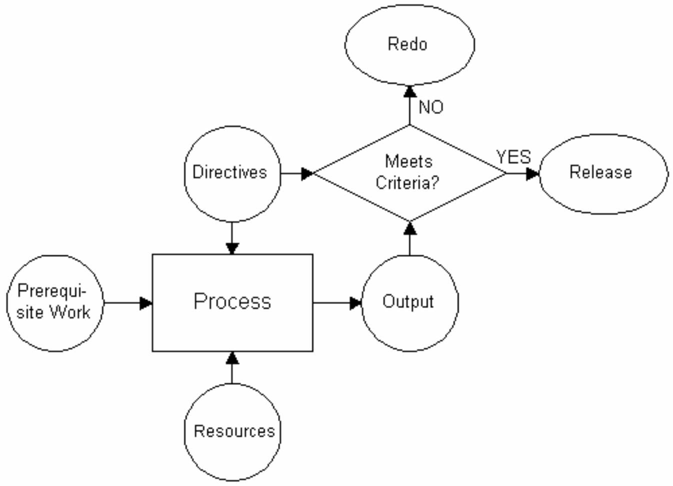

*Figure 3: Activity Definition Model (LCI 2004)*

As a guide for Work Structuring, Ballard (1999) developed the following questions:

- In what chunks will work be assigned to specialists?
- How will work chunks be sequenced?
- How will work be released from one production unit to the next?
- Where will de-coupling buffers be needed and how should they be sized? (Howell et al. 1993)
- When will different chunks of work be done?
- Will consecutive production units execute work in a continuous flow process or will their work be de-coupled? (Tsao et al. 2000)

Ballard (1999) also identified three types of work flow: engineering, procurement, and construction (Figure 4). Work Structuring determines these work flows, which establish a project's primary construction assembly line and the subassembly lines that feed into it.

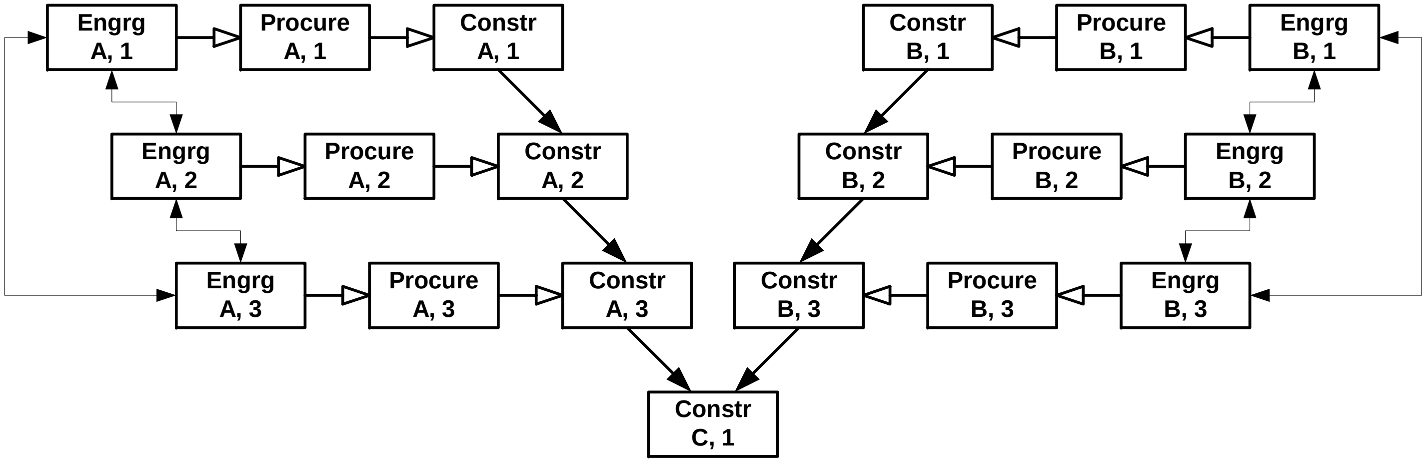

*Figure 4: Engineering, Procurement, and Construction Work Flows (Ballard 1999)*

### 1.2.3 – Customer Order Decoupling Points and Approaches to Product Supply

Customer Order Decoupling Points (CODPs) separate customer-order driven activities from planning driven activities (Wortmann et al. 1997). "Activities upstream of the CODP are driven by planning activities based on forecasts rather than on firm customer orders. Logistics focuses on stocks. Information systems are based primarily on anonymous items, upstream of the CODP. Downstream of the CODP, logistics focuses more on time. Information systems are not only based on anonymous items, but also on customer orders… Different positions of the CODP give rise to quite different production situations" (ibid, p. 59).

CODPs of products found within Work Structures impact the degree of difficulty for (1) executing work chunks reliably and (2) restructuring work to manage changing project conditions. Thus, project planners might gauge the difficulty of implementing alternative Work Structures based on their products' CODPs.

CODPs establish, among other things, (1) how and when fabricators make components and products and (2) which project participants bear the cost of lead time (Melnyk and Denzler 1996, p. 82).

- **Lead time –** The duration from order to receipt of product by the customer.

Thus, CODPs set the tone for customer relations and influence the range of products that can be offered to customers.

In general, project participants need to design, fabricate, assemble, and deliver products before they can be used on projects. More specifically, fabrication involves transforming raw materials into products whereas assembly involves combining prefabricated products. Based on the outline of customer driven manufacturing by Wortmann et al. (1997) and a discussion of the types of ‘making’ by Ballard and Arbulu (2004), we distinguish approaches to supply as follows:

- **Made to Stock (MTS) –** When companies design, fabricate, and assemble products before the CODP and deliver products after the CODP.
- **Assembled to Order (ATO) –** When companies design and fabricate products before the CODP and assemble and deliver products after the CODP.
- **Fabricated to Order (FTO) –** When companies design products before the CODP and fabricate, assemble, and deliver products after the CODP.
- **Engineered to Order (ETO) –** When companies design, fabricate, assemble, and deliver products after the CODP.
- **Made to Order (MTO) –** When products are not made to stock and instead are assembled to order, fabricated to order, or engineered to order.

Figure 5 illustrates the relationship between these product supply approaches based on the location of their CODPs.

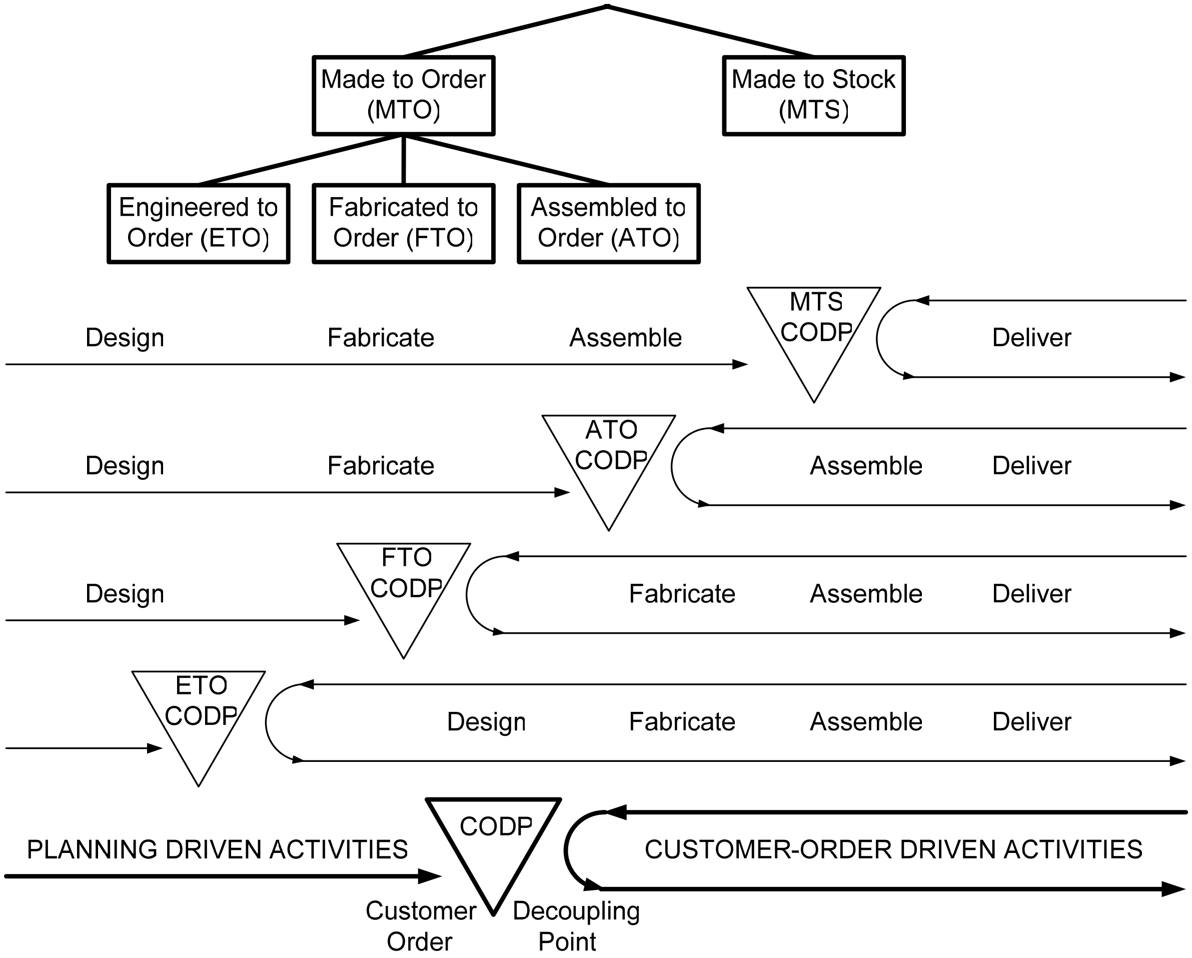

*Figure 5: Product Supply Approaches Based on CODP Locations (based on Wortmann et al. 1997) (“CODP” = Customer Order Decoupling Point)*

Work Structures consisting of products with relatively more upstream CODPs (i.e., CODPs that occur earlier in product development, e.g., ETO) may prove to be more difficult to implement than Work Structures consisting of products with relatively more downstream CODPs (i.e., CODPs that occur later in product development, e.g., MTS). We will investigate this relationship in our case studies.

### 1.2.4 – Specialty Contractor vs. Subcontractor

We use the term ‘specialty contractor’ as opposed to ‘subcontractor’ to distinguish project roles from contractual relationships:

- **Specialty contractor** – A company that “performs construction work [which] requires skilled labor from one or at most a few specific trades (e.g., electrical, plumbing, HVAC, roofing, iron work, and concrete) and for which they have acquired special-purpose tools and equipment as well as process know-how” (Tommelein and Ballard 1997). Specialty contractors may contract with owners, construction managers, general contractors, or other specialty contractors.
- **Subcontractor** – A contractor (often a specialty contractor) hired to work for another contractor (often a general contractor). The use of the term ‘sub’ implies a contractual hierarchy.

### 1.2.5 – Level of Influence

How might the benefits of Work Structuring be better achieved on projects? Practitioners recognize the value of spending more time in design development to improve overall project delivery. However, the nature of contracts, project deliverables, and meetings may make it difficult for them to effectively develop a range of alternative Work Structures because: (1) Contracts can foster strong allegiances among project participants which prevent them from revealing ideas for improving overall project delivery, (2) The structure of project deliverables may delay the release of pertinent information to fabricators who are producing components with long lead times, and (3) Meetings may facilitate participation but not necessarily interactive problem-solving by all project participants. As a result, practitioners should revisit the Level of Influence concept:

- **Level of Influence –** Concept in which commitments made during the early phases of a project have “orders of magnitude greater influence on what later expenditures will actually be” (Paulson 1976b).

Researchers can thus help practitioners determine where and when to focus their time and energy in Work Structuring to improve efficiency of project delivery.

### 1.2.6 – Negative Iteration and Last Responsible Moment

Ballard (2000a) found “informal surveys of design teams have revealed estimates as high as 50% of design time spent on needless (negative) iteration.”

- **Negative Iteration** – “Iteration that can be eliminated without value loss” (Ballard 2000a). It is commonly found in design processes.

Postponement is a strategy for reducing negative iteration by preventing premature decisions. Project participants can also “systematically defer decisions until the Last Responsible Moment”:

- **Last Responsible Moment –** "The point at which failing to make the decision eliminates an alternative" (Ballard 2000a, Ballard and Zabelle 2000).

Lead times for products of alternative Work Structures may provide insight into the Last Responsible Moment for critical decisions. In addition, we should strive to reduce lead times for all product types (Ballard 2000a). Then, if project participants selected a Work Structure containing products that have more downstream CODPs, they could take advantage of "shorter, less variable lead times [that] would allow delaying design decisions to accommodate customer needs for late-breaking information, or could be used to shorten overall project durations" (Ballard 2000a).

## 1.3 – Hypotheses

This dissertation seeks to confirm or refute the following hypotheses:

- Although Work Structuring is an established practice, it is relatively new as a theoretical concept. A theoretical concept is needed to improve practice.
- Adopting a methodical Work Structuring approach facilitates better integration of product and process design.
- Standardization is an effective Work Structuring strategy.
- Because of their expertise in emerging technologies and direct impact on project performance, involvement of downstream players (e.g., specialty contractors and fabricators) in upstream Work Structuring decisions improves product and process design integration.

## 1.4 – Research Goal

Our primary research goal is to apply a framework for studying the concept of Work Structuring. Although the Work Structuring concept is not new – practitioners have been "structuring work" for as long as construction projects have been in existence (Tsao et al. 2004) – we need a formal framework so that practitioners and researchers will have a common language for structuring practice, research, and teaching as well as interpreting results. In particular, a framework requires:

- **Language** – terminology to describe Work Structuring concepts
- **Structure** – methods to represent *who* is doing *what* and *when* within Work Structures. In our case studies, we experiment with different approaches to show structure including: swim lane diagrams, process maps, contractual relationship diagrams, dependency structure matrices, and work responsibility tables.
- **"Operators" for analysis** – methods to evaluate and compare Work Structures. This includes developing indicators and metrics that help project participants make better Work Structuring decisions throughout project delivery.
- **Applications** – demonstration of the Work Structuring concept and use of the framework on projects with varying scope and size.

Application in different environments may reveal commonalities across projects which in turn guide the identification of organizing principles and techniques to improve product and process design integration.

## 1.5 – Research Scope

The scope of this research includes:

- The formulation of a Work Structuring framework based on previous research and practice on capital facility projects.
- The refinement of the Work Structuring framework based on 3 case studies from capital facility projects.
- An emphasis on the structures of supply systems over the structuring of on-site processes and operations.

In particular, we will follow project delivery from identification of project purposes in the Project Definition phase through installation in the Lean Assembly phase (Figure 6). With each case study moving further upstream in the LPDS, we will investigate the project delivery roles of regulatory agencies, owners, architects, engineers, general contractors, specialty contractors, fabricators, and distributors.

## 1.6 – Research Objectives

In each case study, we try to achieve the following objectives:

- **Understand current Work Structuring practice**

Our research investigates how Work Structuring, i.e., the project's organizing principle, is managed across company boundaries as project participants shape a project's scope of work, work processes, organizational structure, etc.

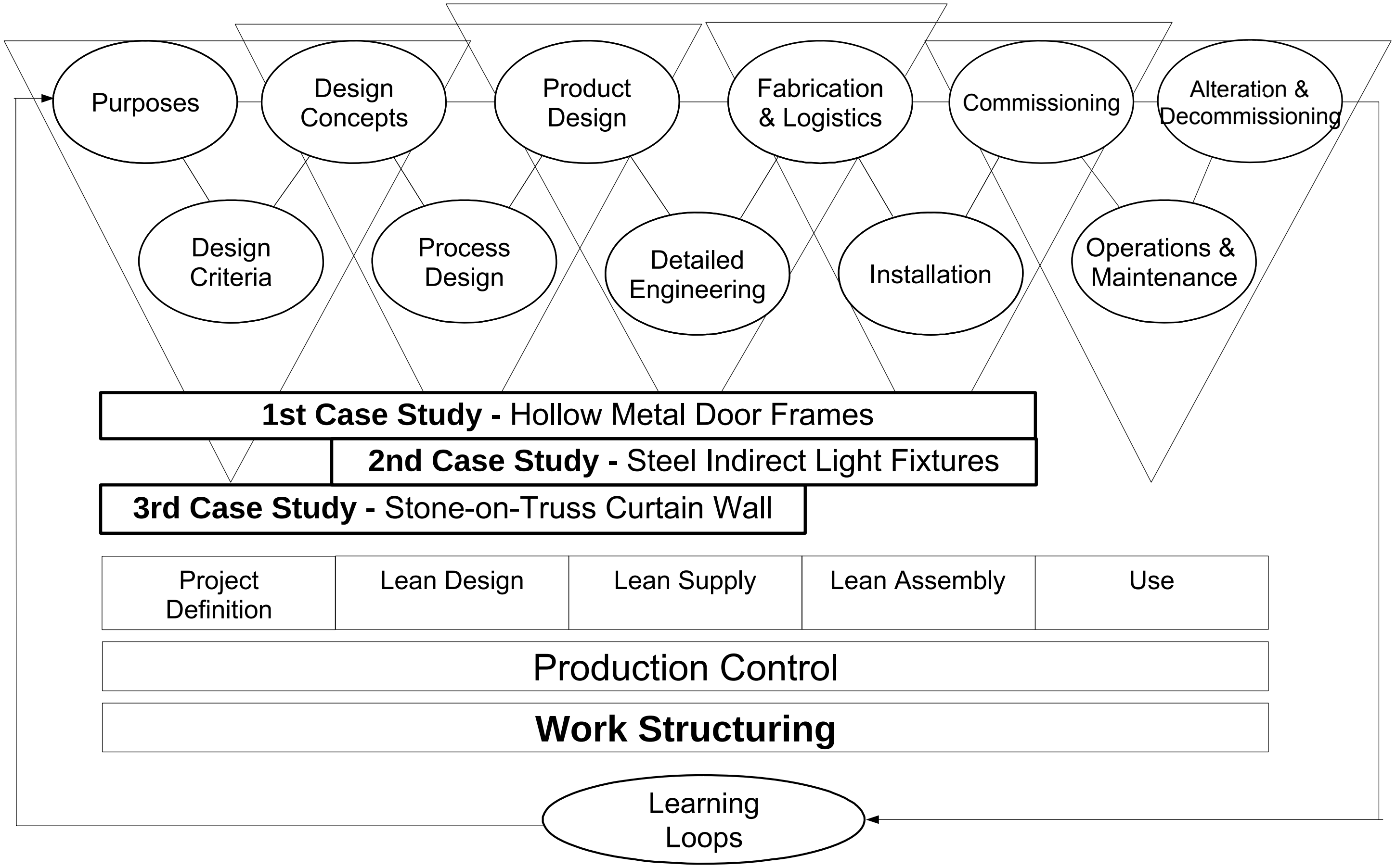

*Figure 6: Research Scope and Case Study Coverage (adapted from Ballard 2003)*

The owner's definition of project scope that emerges during the Project Definition triad of the LPDS heavily influences the direction of Work Structuring by emphasizing the areas of project performance that are most important to the owner (e.g., accelerated schedule). This emphasis may then limit the alternative Work Structures that project participants can consider.

During the Lean Design triad of the LPDS, architects and specialty designers try to consider numerous alternative Work Structures. However, if they limit their product design choices due to schedule pressures, they may make unintentional purchasing decisions resulting from hasty decisions in product design (Sadonio et al. 1998). Furthermore, purchasing decisions define the structure of supply chains and process designs because each product has certain lead times and installation requirements (Gil et al. 2001). By studying current practice, we hope to understand how architects and specialty designers make critical design decisions so that we can recommend how they should pull relevant information from general contractors, specialty contractors, and fabricators before they settle on a specific design direction.

During the Lean Supply and the Lean Assembly triads of the LPDS, fabricators and contractors encounter problems while executing the planned Work Structure, especially if design professionals are not held accountable for managing "means and methods". This traditional separation of responsibility for product and process design forces fabricators and contractors to develop "fixes" to the planned Work Structure. We will investigate these incidents to help architects and engineers learn from current projects and adjust their Work Structuring approach on future projects.

- **Develop methodology for Work Structuring practice**

By developing a Work Structuring framework, we hope to demonstrate which factors and considerations are critical for generating better alternative Work Structures. In particular, we will investigate how project participants can structure work for value generation as well as continuous work flow. In addition, we will illustrate how project participants can reveal their capabilities to support the Work Structuring effort without compromising their competitive advantage. Then, projects might be better positioned to improve product and process design integration.

## 1.7 – Research Questions

The following questions drive this research:

- How do we recognize when project participants are Work Structuring?
- What methods help to reveal Work Structuring activities?
- What are barriers to the development of better Work Structures?
- Which principles and techniques facilitate better Work Structuring?
- What steps should be included in a structured Work Structuring approach?
- What is the impact of using a structured Work Structuring approach?
- Should different Work Structuring approaches be used for Work Structures with different Customer Order Decoupling Points (CODPs)?

- Should design professionals “pull” information from fabricators and installers, or is the most effective working structure that of a team?

## 1.8 – Research Methodology

### 1.8.1 – Research Process

Our research methodology includes the following steps, listed more or less in the order they were executed:

- In-person interviews with local general contractors and specialty contractors to understand current state of practice.
- Literature review of Work Structuring-related research.
- Development of hypotheses to advance Work Structuring research and address problems in current practice.
- Development of research goal, scope, objectives, and questions to support hypotheses.
- Decision to use case study method to achieve research goal and objectives.
- Selection of case studies to demonstrate concept applicability.
- One-on-one telephone and in-person interviews with practitioners from the prison construction-, architectural lighting-, and curtain wall industries.
- Job-site visits to observe installation of case study products.
- Off-site fabrication visits to observe production of case study products.

- Attendance of design development and construction coordination meetings.
- Development of case studies.
- Validation of case study representation accuracy through follow-up correspondence with practitioners.
- Presentation of intermediate research findings at conferences, and receiving of feedback from colleagues.
- Development of cross-case comparison.
- Formulation of research conclusions and recommendations for future research.
- Reporting of research results in journal papers.
- Dissertation writing.

To better understand AEC practice, we sought out practitioners who (looking back on a past project or looking forward to an upcoming project) could provide insight into: (1) different approaches for structuring work, (2) types of resources typically used on projects, and (3) constraints to changing current practice. As we developed the case studies, we checked back with practitioners to make sure we accurately represented their input. In particular, we interviewed owners, architects, engineers, general contractors, specialty contractors, distributors, and fabricators to:

- Understand the rationale behind specific project requirements.
- Investigate how they influence or make product and process design decisions.
- Determine how they negotiate trade-offs in product and process design.

- Study how they sequence, fabricate, and install project systems and components.
- Formulate a methodology for Work Structuring.

### 1.8.2 – Use of Case Studies

This research uses case studies to study the concept of Work Structuring. Case studies use “both qualitative and quantitative methodologies to help *understand* phenomena” (Meredith 1998), so they are conducive to theory building. Specifically, our case studies focus on different project phases and pertain to systems of varying size and complexity. We thereby hope to demonstrate the applicability of Work Structuring and “help extend the generalizability of the results” (Meredith 1998).

### 1.8.3 – Selection of Case Studies

Customer Order Decoupling Points (CODPs) of products found within Work Structures impact the degree of difficulty for executing and restructuring work. For example, executing Work Structures containing primarily Made to Stock (MTS) products would likely be easier to manage than executing Work Structures containing primarily Engineered to Order (ETO) products. Consequently, we selected case studies that involved products with different CODPs to demonstrate the applicability of the Work Structuring concept.

## 1.9 – Dissertation Structure

Chapter 2 reviews literature on research related to Work Structuring. In particular, we highlight early examples of Work Structuring, research in project management, and research in lean production and lean construction.

Chapter 3 describes the first case study in Work Structuring. Beginning in the Lean Assembly triad of the LPDS (Figure 6), the Hollow Metal Door Frames case study (i.e., “Case 1”) discusses how project participants failed to adopt a systems-oriented perspective, working instead within a purchasing mentality (Tsao et al. 2000). Since supply designs limited assembly options, Case 1 explores how to restructure the integration of product and process design. In particular, Case 1 investigates standard practice and helps formulate an initial framework for Work Structuring research.

Chapter 4 describes the second case study in Work Structuring. Focusing on the Lean Supply triad of the LPDS (Figure 6), the Steel Indirect Light Fixtures case study (i.e., “Case 2”) explains how efforts in new product development and supply chain management by the fabricator restructured *who* should do *what* and *when* in project delivery (Tsao and Tommelein 2001). In particular, Case 2 illustrates how a fabricator used understanding of process to guide the design of its products. Thus, Case 2 highlights effective Work Structuring practice and provides feedback on the initial framework.

Chapter 5 describes the third case study in Work Structuring. Concentrating on the Lean Design triad of the LPDS (Figure 6), the Stone on Truss Curtain Wall case study (i.e., “Case 3”) investigates missed opportunities for global optimization during design collaboration meetings. Case 3 presents a methodology to help project participants manage the relationship between upstream design decisions and downstream production processes (Tsao and Tommelein 2004). In particular, Case 3 experiments with methods to make Work Structuring issues transparent during meetings.

In closing, Chapter 6 evaluates cross-case findings and additional lessons learned. Then, Chapter 7 provides an assessment of contributions to knowledge and suggestions for future research in Work Structuring.

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# CHAPTER 2 – LITERATURE REVIEW

## 2.1 – Early Examples of Work Structuring

Work Structuring is not a new idea. It is an idea that has been around for a long time, even though the related literature appears to be lacking in descriptions of a formal framework and methodology to support its systemic development.

To illustrate how practitioners and researchers have been "structuring work" in the past, we review early papers from the American Society of Civil Engineer's Journal of the Construction Division (which later became the Journal of Construction Engineering and Management) for Work Structuring examples and discussion. We selected this journal because it provided a well-documented, historical perspective into the evolution of AEC industry practice in the U.S. during the post-World War II era, before the ubiquitous use of computers. During this period, practitioners regularly contributed case studies which described the challenges they faced on the projects of their time.

Work Structuring coordinates supply chain, product, process, and operations designs to improve overall project performance. Thus, we selected a sample of papers that specifically discuss adjusting at least one type of design to influence another type of design or overall project performance.

### 2.1.1 – 1950s

Whitman (1957) discussed the pros and cons of choosing welded versus riveted connections on a missile testing facility. Although a riveted structure "has the advantage of standardization of design and fabrication, resulting in lower unit cost and greater ease of inspection and testing during construction," project planners decided to build a welded structure because of potential advantages in weight and strength. During fabrication, some details required uncommon shop practices. However, the resulting lighter members helped reduce construction costs for supporting structures. Thus, a change in product design complicated operations design but improved overall project quality and budget.

Merchant (1959) documented the design and construction of a steel truss bridge located adjacent to an existing bridge. On the project, planners considered two alternatives for pier details. The first alternative used "dumbbell type piers on timber foundation piling [that were constructed] within sheet pile cofferdams." The second alternative used "a precast shell carried on timber foundation piling filled with tremie concrete to… the top of the precast portion of the pier." To reduce project costs, the contractor decided to use the precast shell type pier. Then, "the pier sections were cast in a central casting yard… [and] the various pier sections were cast in steel forms and were steam cured." The pier sections typically used a 22.8 MPa (3,300 psi) concrete except in the case of the large conical sections located near the base of the piers. In those situations, the conical sections used lightweight concrete to "keep the weight within limits that could be handled by the contractor's floating equipment." Consequently, planners modified the product design to better support the process and operations designs to improve project performance in terms of safety and budget.

### 2.1.2 – 1960S

Low (1960) detailed the retrofit of a railway tunnel. Above the tunnel, a saturated silt layer had to be stabilized to prevent damage to utilities and adjacent buildings. To address this problem, planners considered various process and operations designs including (1) the “open cut method using steel sheet piling and bracing”, (2) “injecting either grouts… or chemical solutions”, (3) draining the silt, and (4) “circulating a freezing solution through pipes driven into the silt.” They eliminated the first few alternatives because (1) the open cut method would “cut through too many services… [and] require[d] very heavy bracing”, (2) “the permeability of the silt was low, [so] its properties could not be changed by [injection]”, and (3) “leaking water pipes in the vicinity… [most likely] would continue to do so during attempts at drainage.” Planners chose the soil freezing alternative because it supported adjacent buildings, allowed “excavation to proceed using regular tunneling methods”, and provided flexibility in the location of freezing points to avoid utilities. Although the contractor found soil freezing to be an expensive process, the project benefited from safer working conditions, no unexpected difficulties (i.e., increase in work reliability), and an accelerated schedule.

Campbell (1961) discussed a low bidder’s use of fly ash with portland cement in the construction of the concrete sections of a lock. The use of fly ash improved the product design by reducing leaching, efflorescence (i.e., development of crystalline salt deposits), and drying shrinkage. It helped reduce the water-cement ratio to increase the life and durability of the concrete. In addition, the use of fly ash increased workability and improved the finishing qualities of the concrete.

Saul (1962) described the planning process for the construction of a hydroelectric power plant. During the initial planning phase, the project's "construction group prepared preliminary schedules, possible layouts of temporary facilities, general lists of construction equipment, and tentative manpower curves." The estimating group worked on "determining the total cost and seeking possibilities for savings in quantities, types of material, and construction methods." The design group investigated alternative product designs (e.g., layouts and types of dams) with an emphasis on "reducing the quantities and costs while maintaining the required design standards." Staying in contact during the initial stages of planning, the construction, estimating, and design groups altered or eliminated some alternatives due to "excessive costs, impractical construction procedures, or unfeasible design." Later, during the detailed planning phase, project participants introduced safety as a "prime requisite" as they further developed the operations designs. Thus, this project established a Work Structuring process with quality assessment metrics for evaluation. Then, the project participants continued to adjust the product, process, and operations designs to improve budget and schedule performance.

Mullen (1963) highlighted a project involving new locks and dam construction, dredging, and alterations to existing structures. During the early stages, the contractor found that the foundation conditions made de-watering difficult, so the design group consulted with three de-watering companies before rewording the specifications for the later stages of the project. Accordingly, the design group avoided defining the contractor's means and methods by setting "forth requirements in the specifications that would assure an excavation procedure so that concrete could be placed in the dry while still permitting bidding contractors to exercise their best ingenuity, planning, and experience in bidding in order to successfully perform [the de-watering].” Thus, to improve project quality, the design group modified the product design to facilitate increased flexibility in developing the process and operations designs. This practice also reduces uncertainty to bidders and supposedly reduces submitted bid prices.

Gleason and Ranieri (1964) discussed a resources planning and scheduling method (RPSM) that used the critical-path method (CPM) to assist with resource leveling. Although RPSM used trial-and-error to refine the CPM schedule, they noted it provided a fast and accurate technique for resource leveling by combining managerial judgment with a computer system that contained relevant information. Furthermore, they believed RPSM is “valuable even for a contractor in a labor market of good supply, for it is economical and important for him to allocate his crafts as smoothly as possible over the life of the project and to build and maintain a reputation as a dependable employer.” As a result, they used sequencing to balance, in a narrow sense, supply chain design with process design to improve working conditions and schedule performance. Today many computer-based algorithms exist based on heuristics or other optimization techniques to assist with resource leveling and scheduling.

Kavanagh and Tung (1965) described the design and construction process for a large radio telescope. At one point, project planners had to decide on the shape of the feed platform (i.e., triangular or Y-shaped) suspended over the center of the radio telescope and the material used for the towers that held up the feed platform (i.e., steel or concrete). Studies revealed “that a triangular steel platform suspended from concrete towers would be more economical, simpler and faster to erect, and would yield better performance.”

Therefore, the project demonstrated how modifying the product design to improve the operations design can result in better quality, schedule, and budget performance.

Ammann (1966) detailed the planning process for the design and construction of the Verrazano-Narrows Bridge. In particular, “unusually thorough design studies were made to develop effective and economical details… Certain important details were studied on full-scale models to demonstrate their practicability and ease of fabrication, erection, and maintenance.” Since the Verrazano-Narrows Bridge became the world’s longest suspension span when it opened, the planning thoroughness may be due in part to a desire to avoid any mistakes that contributed to the 1940 collapse of the Tacoma Narrows Bridge. Also, “other improvements which effected savings in cost and in time of fabrication and erection were the use of high-strength low-alloy rivets and of high-tensile bolts for the field connections of structural steel members in place of rivets.” Consequently, by modifying the product design to better support operations, the design group improved overall project performance in terms of safety, schedule, and budget.

Low (1967) examined replacing trucks with a conveyor system to move fill materials 6.4 km (4 miles) for the construction of a dam. Since other projects began using similar systems successfully, the contractor decided to experiment with a conveyor system because it had great potential for reducing cost. Despite some minor operation problems, “the contractor was able to maintain a high production rate, largely because of an excellent program of preventive maintenance.” Thus, by changing the operations design to improve process design, the contractor was able to improve project performance in terms of both schedule and budget.

### 2.1.3 – 1970s

Gurfinkel (1970) documented the design and construction of a 9-story campus building which used prefabricated reinforced concrete columns that spanned multiple stories. Due to shipping limitations, the maximum column length was 19.5 m (64 ft) which spanned 5-stories, so the building also required a set of columns that spanned 4-stories. These columns helped reduce “the number of ‘erect column-lift slabs’ cycles which reduced erection costs and time.” The use of two sets of columns “also decreased the number and total cost of column connections.” By developing a product design that took advantage of the capabilities of the precast fabricator, the project was able to adopt a more efficient process design and subsequently improved overall schedule and budget performance.

Bartlett and Ramsay (1971) described the use of precast concrete tunnel linings for a subway project. Initial reports indicated concrete may provide an overall project cost savings of 25% in comparison to using cast iron, so the project conducted a First Run Study with an installation of 50 bolted and 50 unbolted concrete rings.

A First Run Study examines “the first run of each type of craft operation… to explore alternative ways of doing the work. The result will be a performance standard (that can be used) as a challenge to meet or beat the best done thus far” (Ballard and Howell 1994). First Run Studies often take on the form of “productivity improvement” efforts (e.g., Oglesby et al. 1989) because they accept the current design and develop solutions that work within existing contractual agreements.

The subway project’s First Run Study found (1) the bolted rings compared favorably with cast iron rings in terms of tunneling progress, and (2) the unbolted rings often cracked due to binding and loading problems between segments. However, concrete linings leaked when used under a head of water, so the project decided to use both cast iron and bolted precast concrete linings. Since the project required at least 7,500 concrete rings, a precast plant modified its facilities to accommodate over 200 steel forms for the production of concrete segments. Each ring consisted of 8 segments, so with 200 forms, the precast plant could produce about 25 complete rings each day. Thus, by changing the operations design of its fabrication facilities, the precaster improved its ability to supply materials to the contractor. At that time, the procurement cost of concrete rings was $300 each and cast iron rings was $730 each. Although concrete rings cost more to install, they still provided an overall savings of at least $300 per ring. As a result, by reviewing and adjusting the product and process designs, the project was able to save more than $1,500,000 for every mile of twin subway tunnel.

Byrne (1972) discussed “the business of avoiding, resolving, or handling the problems often attending contractual relations” in large dam construction. He emphasized that many problems between designers and contractors can be eliminated in the design stage. For instance, “bidders should aggressively question the actual need for those design details that limit or prevent the use of cost saving construction procedures.” However, contractors may hesitate to do this for fear of exposing their bid strategy. One example of this is concrete form alignment. Concrete form alignment affects cost because “the tighter the tolerances, the greater the number of ties that are needed, and also, a larger amount of skilled labor is consumed trying to [meet alignment requirements].” Then, sometimes the “demanded tolerances were beyond the normal means and accuracy of measurements.” Instead, Byrne recommended that alignment “be designed into the metal parts rather than into the concrete surfaces" because compared to concrete, contractors can achieve tighter tolerances with metal. Thus, by adjusting the product design to better support process design, projects can improve overall budget performance.

Nussbaum (1973) described tunneling methods for materials incapable of supporting themselves. Project specifications defined different rock classes that a contractor could encounter as tunneling progressed. For each rock class, a design drawing further outlined "required shotcreting and wire fabric, local protection and system anchoring, steel supports, drainage and other details." The design also identified the maximum time allowed between excavations and concreting, "the maximum amount of explosives to be used, [and] safety measures at the face." The contractor then decided upon the appropriate excavation method and use of a tunneling shield. The designers thus modified the product design to regulate the process design and help improve overall project safety and budget performance.

Grimm (1974) summarized recommendations from bricklayer productivity research results carried out by more than 200 researchers. In particular, Grimm found that "architects should simplify wall design" and "contractors should provide mechanical aids to brick and block-laying, adjustable scaffolding, weather protection, and improved job organization." Doing so "could increase the quantity and quality of work output by 50%." Therefore, by modifying product and operations designs, architects and contractors can create safer working conditions and achieve better results in both quality and schedule.

Hollingsworth (1975) reviewed developments in engineering, materials, fabrication, construction, and aesthetics of steel arch bridges. In one example, he discussed how a contractor obtained approval to substitute a new type of steel for the bottom chord of an arch truss. The new steel was a carbon-manganese composite that was “about 50% stronger than carbon steel and considerably cheaper than the [originally specified] nickel steel.” With this modification, the contractor adjusted the supply chain to improve the product design and generated improvements in overall project quality and budget.

Paulson (1976b) described “the interrelationships between engineering design, construction, and operating costs for a facility.” Specifically, he provided hypothetical examples of how product design decisions can influence supply chain, process, and operations designs (e.g., “It was the designer who may or may not have packed the reinforcing steel so densely that concrete cannot be placed by economical procedures. It was the designer who may or may not have specified nonstandard sizes, impossible formwork configurations, techniques requiring incompatible mixtures of labor crafts, bronze fittings where galvanized were more than adequate, etc.”), thus resulting in longer project durations and increased construction costs.

Hester (1978) provided “specific guidelines and practices for construction with air-entrained concrete, and the resolution or minimization of production problems.” For example, to improve mix uniformity and stability of entrained air voids, contractors should simultaneously add and blend cement and aggregates before adding air entraining agents and admixtures. In addition, mixers that employ a folding and kneading action are more effective at entraining air. Therefore, by refining the process and operations designs, contractors can increase overall project quality.

### 2.1.4 – Conclusions from Early Examples

From our sample of journal papers, we found the majority of projects described heavy civil projects as opposed to building construction projects – this may be due in part to (1) the United States' emphasis on infrastructure development following the adoption of the Federal-Aid Highway Act in 1956, (2) in heavy civil projects, decoupling of design and construction work is nearly impossible, and (3) the prominence of larger magnitude projects. Summarizing the examples in Table 1, we note that past practice and research have certainly addressed Work Structuring (albeit without a common framework) since most product design choices have process or operations design implications. Thus, in some cases, the architect's design may intentionally or unintentionally influence the general contractor's means and methods.

Saul (1962), in particular, provided the closest example of a Work Structuring approach. Also, the majority of Work Structuring examples discussed positive experiences in practice. Only Paulson (1976b) explored hypothetical Work Structuring experiences with primarily negative outcomes. By investigating problems encountered on actual projects, we can begin to understand the limitations of current project management techniques. Following this approach, our first case study will examine a real world Work Structuring example that experienced negative outcomes.

With this example-based historical perspective in mind, we next examine related project management research.

*Table 1: Early Examples of Work Structuring (“Δ” = Changes, “+” = Positive Impact, “–” = Negative Impact)*

| **REFERENCE** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| Whitman 1957 | | Δ | | – | | + | | + |
| Merchant 1959 | | Δ | + | + | + | | | + |
| Low 1960 | | | Δ | Δ | + | | + | – |
| Campbell 1961 | Δ | + | | + | | + | | + |
| Saul 1962 | | Δ | Δ | Δ | + | | + | + |
| Mullen 1963 | | Δ | + | + | | + | | |
| Gleason and Ranieri 1964 | Δ | | Δ | | | + | + | |
| Kavanagh and Tung 1965 | | Δ | | + | | + | + | + |
| Ammann 1966 | | Δ | | + | + | | + | + |
| Low 1967 | | | + | Δ | | | + | + |
| Gurfinkel 1970 | | Δ | + | | | | + | + |
| Bartlett and Ramsay 1971 | + | Δ | Δ | Δ | | | | + |
| Byrne 1972 | | Δ | + | | | | | + |
| Nussbaum 1973 | | Δ | + | | + | | | + |
| Grimm 1974 | | Δ | | Δ | + | + | + | |
| Hollingsworth 1975 | Δ | + | | | | + | | + |
| Paulson 1976 | – | Δ | – | – | | | – | – |
| Hester 1978 | | | Δ | Δ | | + | | |

## 2.2 – Project Management

### 2.2.1 – Coordination and Collaboration

Our case studies seek to meet Higgin and Jessop's (1963) recommendation "that research be undertaken on the basis of protected experiments into the interdependent operations of the building process concurrently with studies of the roles and relationships of the building team members involved." Since "no single tool, by itself, is accurately capable of fully modeling both construction system and construction work processes" (Kartam et al. 1997), we will experiment with various techniques for modeling supply chains, contractual relationships, flows of information, and flows of goods associated with each case study.

Higgin et al. (1966) noted the importance of reducing "the uncertainties which result from the present artificial division between design and construction planning cutting across the information feedback link which is so vital to the effective functioning of the building process." Thus, we will examine how to increase transparency between design and construction planning so that project participants can improve their efforts in product and process design integration.

Coordination meetings are important facets of project planning and execution because they help project participants improve their perception of reality (Hensey 1981) (Figure 7). Without a common and reasonably accurate perception of reality, project participants risk working towards conflicting goals or following a single design direction that actually conflicts with the owner's needs or values. Thus, Case 3 will study how coordination meetings contribute to product and process design integration.

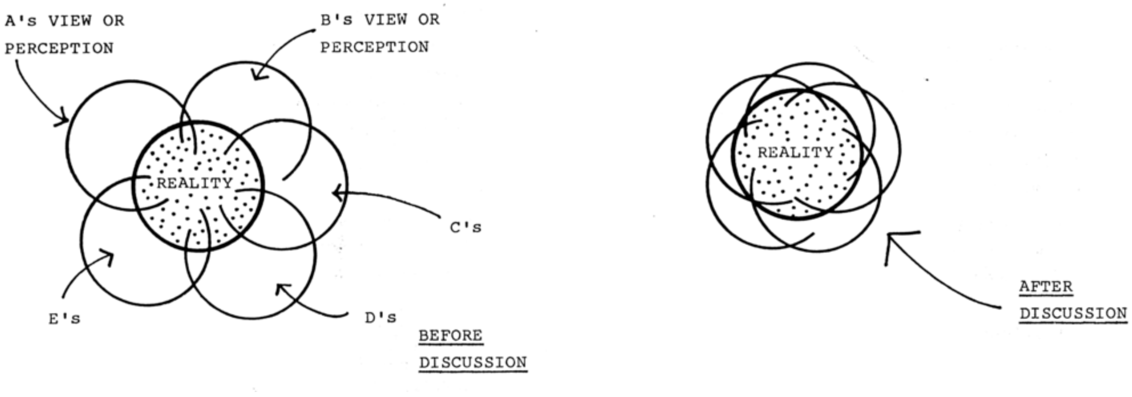

*Figure 7: Evolution of Perception of Reality by Project Participants (Hensey 1981)*

To improve our understanding of Work Structuring, we will investigate how project participants determine: (1) the method of generating value for the owner, (2) required work chunks, (3) when to execute required work chunks, (4) which project participants would be best suited to execute required work chunks, and (5) how project participants handoff work. These aspects of Work Structuring are similar to the components of coordination identified by Malone and Crowston (1990) (Table 2).

*Table 2: Components of Coordination (Malone and Crowston 1990)*

| **Components of Coordination** | **Associated Coordination Processes** |
|---|---|
| Goals | Identifying goals |
| Activities | Mapping goals to activities<br>(e.g., goal decomposition) |
| Actors | Selecting actors<br>Assigning activities to actors |
| Interdependencies | "Managing" interdependencies |

In particular, our case studies in Work Structuring will examine the coordination and group decision-making processes as outlined by Malone and Crowston (1990) (Table 3).

Future research in Work Structuring might examine the communication and perception of processes that underlie coordination.

*Table 3: Processes Underlying Coordination (Malone and Crowston 1990)*

| Process Level | Components | Examples of Generic Processes |
|---|---|---|
| Coordination | Goals, activities, actors, resources, interdependencies | Identifying goals, ordering activities, assigning activities to actors, allocating resources, synchronizing activities |
| Group decision-making | Goals, actors, alternatives, evaluations, choices | Proposing alternatives, evaluating alternatives, making choices (e.g., by authority, consensus, or voting) |
| Communication | Senders, receivers, messages, languages | Establishing common languages, selecting receiver (routing), transporting message (delivering) |
| Perception of common objects | Actors, objects | Seeing same physical objects, accessing shared databases |

Project collaboration is influenced by the level of proximity between different project participants “along four dimensions: geographic, organizational, cultural, and electronic” (Fine 1998). The closer project participants are in terms of these dimensions, the more likely they can handle “concurrent design of products, processes, and capabilities.” With increase in such agility, project participants may become more capable of managing Work Structuring effectively during changing market and project conditions.

Lottaz et al. (1999) suggested “the use of constraint solving to express possibly large families of acceptable solutions in order to facilitate and abbreviate the negotiation process.” By adopting this approach, Work Structuring can benefit from a broader consideration of alternatives that may yield more effective methods of value generation. Then, by considering solution spaces instead of single solutions, project participants can postpone production decisions until the Last Responsible Moment to minimize rework and generate greater value resulting from last-minute changes.

Buntrock (2001) introduced 4 models of design development typically found on projects in Japan based on: (1) project participants that are responsible or provide input for each design phase, (2) influence of construction considerations on design development, (3) aesthetic innovation found in components, and (4) performance innovation found in components or systems. Table 4 lists project participant involvement during each design phase to provide a comparative measure for the degree of coordination and collaboration found in our case studies. In particular, Model 4 involving architect, fabricator, and contractor input during all phases of design seems most promising in terms of facilitating innovation in Work Structuring.

*Table 4: Models of Design Development in Japan (based on Buntrock 2001)*

| **Design Phase** | **Model 1** | **Model 2** | **Model 3** | **Model 4** |
|---|---|---|---|---|
| *Schematic / Conceptual Design* | Architect | Architect | Architect | Architect<br>Contractor and fabricator input |
| *Design Development* | Contractor | Architect | Architect | Architect<br>Contractor<br>Fabricator input |
| *Construction Documents / Detailed Design* | Contractor | Architect | Architect<br>Contractor and Fabricator input | Architect<br>Contractor<br>Fabricator |

Steward (1981) introduced the use of a design structure matrix (DSM) to assist with coordination. DSM arranges *n* design parameters along the top and left sides of an *n* x *n* matrix. Marked boxes within the matrix indicate the degree of dependency between design parameters. DSM has since been expanded to represent “dependency structure matrices” to encourage application of the process modeling methodology to areas other than design (Browning 1998). DSM helps make assumptions explicit and “shows which information items are dependent on assumptions and where they should be verified” to help “create organizations structured for better information exchange, better division of responsibility, and greater concurrency” (Denker et al. 1999).

Huovila et al. (1995) suggested that DSM “can effectively be used in construction for finding better sequences of design tasks.” They envisioned using DSM to (1) plan and manage design, (2) conduct fast track analysis, and (3) demonstrate impact of changes. After developing an initial DSM to model information flow and illustrate interaction between design decisions (Baldwin et al. 1998, 1999), project participants can use knowledge-based programs to decompose “complex design problems into a suitable multilevel structure based on the multilevel optimization approach” (Rogers 1990) and then employ additional techniques “to schedule and control the design environment” (Hammond et al. 2000, Choo et al. 2004). Consequently, although an initial DSM requires considerable investment to develop, it can help with many facets of Work Structuring including work chunk definition, sizing, and sequencing as well as handoff clarification.

### 2.2.2 – Decomposition of Work

Project planners typically use a work breakdown structure (WBS) to decompose a project into work packages (WPs) to create a framework for project planning, scheduling, and controls (DOD-NASA 1962 p. 26, Halpin et al. 1987 p. 3, Neil 1988 p. 3). Work breakdown may proceed according to the 16 divisions outlined by the Construction Specifications Institute’s (CSI) and Construction Specifications Canada’s 5-digit

MasterFormat system of classification and numbering (Means 1997). Then, project managers may combine a WBS with an organizational breakdown structure (OBS) to assign WP execution responsibilities among project participants, and “automated data-acquisition and data-storage mechanisms” could be employed to “improve the performance of [this] work-packaging model” (Rasdorf and Abudayyeh 1991).

Project decomposition helps planners visualize a project as a collection of manageable pieces. However, when planners use WBS to decompose a project so that they can manage it at a specific level of detail (e.g., Level 3 in Figure 8), they may inadvertently encourage local optimization over global optimization because (1) they have a contracting bias or (2) project participants have difficulty seeing how their work impacts the overall project. Instead, Work Structuring should use WBS to identify the main (e.g., final assembly at the job-site) and sub-assembly (e.g., fabrication of modular units) lines in Work Structuring. Thus, Work Structuring might begin with decomposition but then adjust the WBS to identify resource dependencies between elements of work at different levels of detail. This allows planners to identify how higher levels of work (e.g., “1A”) may be dependent on both medium levels of work (e.g., “2B” and “2C”) and lower levels of work (e.g., “3D”). Then, project participants will be able to more accurately visualize the main assembly line (e.g., “3D”, “2B’, and “2C”) and determine how sub-assembly lines must perform to ensure that the main assembly line executes as planned.

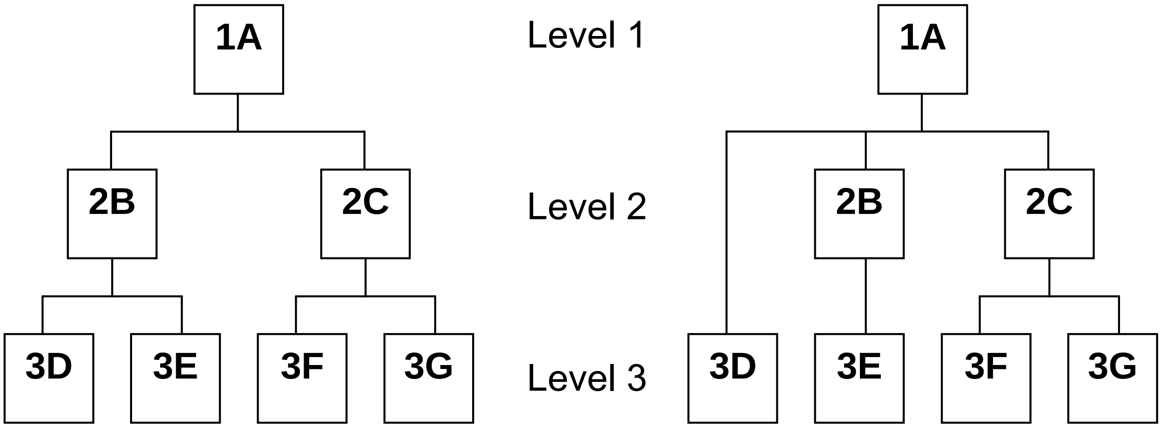

*Figure 8: Traditional WBS vs. Adjusted WBS for Work Structuring*

In managing the WBS process, Raz and Globerson (1998) recognized that "since each WP requires a certain amount of planning, reporting, and control, decomposition of the project into smaller and more numerous WPs increases the workload on the project manager and on the project team." They recommended "that highly interdependent [activities] should be assigned to the same WP, in order to reduce the coupling among work packages and to make it easier to construct the network and to calculate the schedule." This is also achieved in CPM with a technique called 'hammocking.' Thus, this approach might be used as a basis for work chunk management.

For example, if a project has two highly interdependent work chunks with varying execution uncertainties (Figure 9), project participants could combine the two work chunks to manage the work as a single work chunk (Figure 10). Then, after studying the combined single work chunk, project participants might be able to restructure it into 3 work chunks: a work chunk that can be executed reliably (indicated by the blank region in Figure 11) and 2 work chunks that still have varying execution uncertainties (indicated by the striped regions in Figure 11). Then, they would concentrate their efforts on removing constraints to ensure reliable execution of the uncertain work chunks.

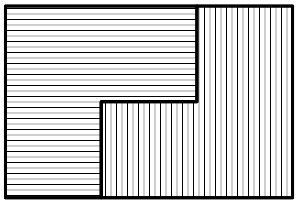

*Figure 9: Two Highly Interdependent Work Chunks*

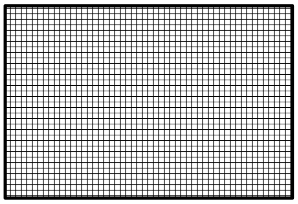

*Figure 10: Combined Single Work Chunk*

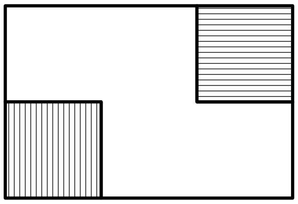

*Figure 11: Isolation of Work Chunks with Greater Execution Uncertainty*

Raz and Globerson (1998) also developed a checklist to guide WP decomposition based on scheduling and costing concerns. They structured the checklist so that "the greater the number of positive answers to the [checklist's] questions, the stronger the justification for breaking down the work package." Considering Raz and Globerson's checklist for WP decomposition, we develop the following checklist to guide work chunk decomposition with an emphasis on execution reliability (NB: Asterisks indicate questions developed or directly adapted from Raz and Globerson's checklist for WP decomposition):

1. Is the work chunk difficult to manage and thus unreliable in terms of execution?
2. Does the work chunk contain areas with greater associated risks or execution uncertainty? Can these areas be isolated as separate work chunks?
3. Is more than one individual responsible for the work contents?*
4. Can you find an individual / team to take full responsibility for this work chunk?
5. Does the work content include more than one type of activity?*

6. Do project participants not involved in the work chunk need information regarding handoffs that occur within the work chunk?
7. Do resources requirements within the work [chunk] change over time?*
8. Are handoffs of work within the work chunk well-defined?
9. Are constraints within the work chunk well-defined?
10. Are there any [handoffs within the work chunk] that can be used to generate a positive cash flow?*

Therefore, Work Structuring can use elements of WBS to begin work decomposition. Project participants would thus identify project phases via milestones in the master schedule and then use phase scheduling "to develop a more detailed work plan that specifies the handoffs between the specialists involved in that phase. These handoffs then become goals to be achieved through production control" (Ballard and Howell 2003).

### 2.2.3 – Production Management

McNally and Havers (1969) noted, "It is relatively easy to note whether or not a man is actually engaged in work; it is much more difficult to establish whether or not he is working efficiently." Workers can be unproductive because their work "is not laid out for optimal performance. These effects are subtle, and extremely difficult to identify." "[W]hen the process is unbalanced, construction time is determined by the slowest production line, which is then critical" (Peer 1974). Thus, by elucidating the building process, we hope to help project participants improve their ability to identify slower production lines that will likely delay overall project progress.

Peer (1974) suggested, “Planning the construction process is not a problem of determining an incidental critical path from arbitrarily fixed activity durations. On the contrary, choice of the critical production lines in terms of cost considerations of limited resources, must be one of the first steps. The rate of progress of all other production lines must be adjusted to that of the line so chosen, which means providing working continuity by making as many activities critical as possible.” By outlining the sub-assembly lines that feed into the main assembly line, project participants can see which production lines require additional resources to ensure that the main assembly line can proceed with continuous work flow. Thus, production planning looks “ahead in terms of *how*,” in contrast to CPM’s inclination to focus on project controls which looks “back in terms of *when*” (Peer 1974). Accordingly, our case studies seek to carry out Peer’s recommendation that “for the construction process to be balanced into a comprehensive system of production, future research must be devoted to the development of construction planning techniques based on input of fundamental production data, e.g., quantities of work, production rates, and other production characteristics.”

Birrell (1978) noted, “The essence of success seems to be perceiving construction as a process, carefully planning it, sequentially moving the subs through the job, fast and clear decision making, creating a construction team spirit which includes respect and trust among team members.” Then, Birrell (1980) observed that few practitioners have questioned the appropriateness of CPM for managing construction projects where “each subcontractor is very interested in the efficient use of his resources on all projects he is working on.” Instead, since CPM was developed to manage military projects that emphasized national security (DOD-NASA 1962), it became more focused on controlling a project rather than efficient resource utilization. Thus, “the typical CPM approach to resource allocation is too simple for construction,” so “the simplest and most appropriate way of [managing construction processes and their] resource requirements in a project is to consider each work squad as a continuous flow.” As case studies in this dissertation will show, by making work flow transparent, Work Structuring can improve the execution of main and sub-assembly lines that exist during various project phases.

Earlier, Paulson (1976b) observed how “all too often [design] decisions are made without the slightest notion as to their impact on construction costs… ‘Value engineering’ clauses in construction contracts are at best after-the-fact remedies for such fundamental oversights.” Birrell (1978) subsequently noted his agreement with Paulson’s (1976b) conclusion that “construction management was not needed for management of construction.” Rather, “for an efficient construction process the quality of whoever manages it is much more important than the relationship – contractual or agent – which exists with the owner.” Furthermore, “The informal construction team is the one which will manage the construction process on most construction sites in North America. It is generally more powerful than any unique organization of contractors, etc. imposed upon the construction team from outside the industry and should always be considered as a starting point for the evolution of any unique organization of construction roles on a future project” (Birrell 1981). In line with this, our case studies look beyond contractual agreements to investigate exactly how project participants manage work chunk identification, sizing, sequencing, and handoffs to ensure reliable execution of work.

We will also investigate how standardization, prefabrication, and modularity can be used to assist production management. McNally and Havers (1967) promoted “the use of standardized sizes of materials… to reduce the job requirements for cutting and fitting." In addition, they suggest "modular designs [can be used to achieve] greater construction productivity." For example, "A typical modular concept for building would begin with a design stage in which all controlling dimensions are established as multiples of 4 inches… The elimination of fractions will reduce the time expended in measuring and checking dimensions, and more material can be precut before it gets to the job-site." Design methodologies were developed in pursuit of the systematic use of such modularity. Thus, we will explore standardization techniques used in Cases 1 and 2.

With regards to prefabrication, McNally and Havers (1967) observed, "During the past few years, prefabricating and preassembling components have increased productivity in the building industry… Prefabrication provides more frequent opportunities for scheduled job repetitions and for work studies which may lead to improved performance. Prefabrication also permits production to continue under adverse weather conditions, with the accumulated inventories stored either on or off the site and subsequently used under more favorable conditions." Additional research have since promoted the benefits of prefabrication (e.g., Kellog 1971, Sprinkel and Morris 1976, Warszawski et al. 1984), and we will discuss at length the role of prefabrication within our case studies.

Ulrich and Tung (1991) emphasized that modularity is a relative property based on: "(1) Similarity between the *physical* and *functional* architecture of the design and (2) Minimization of incidental interactions between physical components." Modularity can consist of the: (1) use of *independent* units, (2) development from *standardized* components, and (3) use of *interchangeable* units to create product variants, so it can take on different forms to "exploit component standardization and… achieve product variety"

(Ulrich and Tung 1991) (Figure 12). Since greater modularization facilitates standardization and interchangeability (Ulrich and Tung 1991), these forms of modularity are helpful to keep in mind during work chunk and handoff definition.

By treating major work chunks as “black boxes,” project participants can then focus on improving definition of handoffs. In addition, while a “black box is… a good tool in interface design since inputs and outputs are clearly defined…, form, fixation principles, and number of contact surfaces should [also] be considered” (Hölttä 2002). Good work chunk definition results in modules that “leverage complementary skills from each company” (Hölttä 2002). When developing modularity on a project, Iansiti (1995) recommended against staggering (1) research explorations, (2) concept evaluation, and (3) module design. Instead, overlapping (1) joint ventures with material suppliers, (2) concept discussion and evaluation, and (3) module design allows for more flexibility where “the emphasis is instead on discovering and capturing knowledge about the interactions between the new uncertain technical possibilities and the system before committing to a particular concept” (Iansiti 1995). Then, project participants can gain an “advantage in environments where technological evolution and competitive requirements are largely unpredictable,” which is often the case on construction projects.

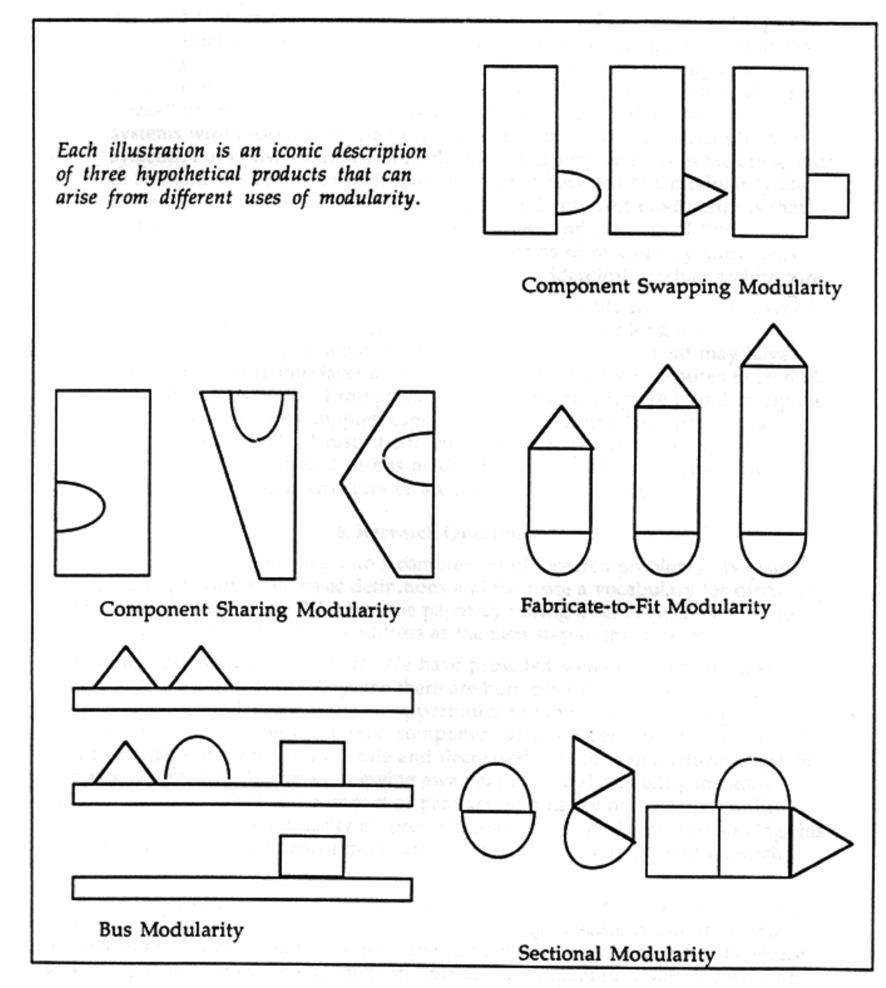

*Figure 12: Different uses of modularity (Ulrich and Tung 1991)*

## 2.2.4 – Role of Specialty Contractors and Fabricators

Specialty contractors and fabricators bring value to projects because they have insight into recent advances in and availability of materials, equipment, and trade skills. Consequently, “We need more involvement of job-site managers – especially foremen – in the planning process” (Olson 1982). However, during project execution, “most subcontractors rely on their own project monitoring efforts rather than placing reliance on the general contractor. To a large extent, this practice exemplifies the fact that many subcontractors do not feel that the general contractor is concerned about what is in the best interest of the subcontractors" (Hinze and Tracey 1994). Thus, specialty contractors and fabricators may hesitate to become involved in project planning to assist the owner, architect, and general contractor. Fortunately, workers have a strong desire to participate (Coffey and Langford 1998), but genuine participation requires genuine decision-making. As a result, we will investigate how and when specialty contractors and fabricators can get involved earlier in Work Structuring so that their input can influence major decisions.

## 2.3 – Lean Thinking

### 2.3.1 – Lean Production

Spear and Bowen (1999) noted, "The tacit knowledge that underlies the Toyota Production System (TPS) can be captured in four basic rules: (1) All work shall be highly specified as to content, sequencing, timing, and outcome, (2) Every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses, (3) The pathway for every product and service must be simple and direct, and (4) Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization." These basic rules should guide the formulation of Work Structuring principles and techniques.

Spear and Bowen (1999) further noted, "By making people capable and responsible for doing and improving their own work, by standardizing connections between individual customers and suppliers, and by pushing the resolution of connection and flow problems to the lowest possible level, the rules create an organization with a nested modular structure… The great benefit of nested, modular organizations is that people can implement design changes in one part without unduly affecting other parts. That's why managers at Toyota can delegate so much responsibility without creating chaos." Hence, our case studies focus on investigating and elevating the role of specialty contractors and fabricators in production system design.

### 2.3.3 – TFV Theory of Production

Koskela (2000, p. 87) found that AEC practice and research regarded production in three different ways: transformation view, flow view, and value generation view. Under the transformation view, project planners see production as a transformation of inputs into outputs (ibid, p. 256). They structure projects as a hierarchy of these transformations and focus on minimizing the cost of each transformation independently (ibid, p. 254). Under the flow view, project planners see production as a flow of material, made up of transformation, inspection, moving, and waiting (ibid, p. 87), and they attempt to eliminate waste from these flow processes (ibid, p. 71). Under the value generation view, project planners regard production as a "process where value for the customer is created through fulfillment of his requirements" (ibid, p. 256), so "transformations and flows are controlled for the sake of the customer" (ibid, p. 78). Since these distinct views of production complemented rather than competed against each other (ibid, p. 255), Koskela combined them to form the Transformation-Flow-Value Generation (TFV) theory of production to provide a "new, theoretical foundation for construction" (ibid, p. 258).

Work Structuring can use the TFV theory of production as a means to gauge whether work has been structured appropriately. When project participants begin planning a project, they will likely first list how inputs transform into outputs. This happens because traditional project management conceptualizes production primarily as a transformation process where: “(1) the total transformation can be decomposed into smaller transformations, (2) the cost of production can be minimized by minimizing the cost of each decomposed transformation, and (3) it is advantageous to buffer production” (ibid, p. 49). Then, they can tackle the more complex tasks of achieving continuous work flow throughout design, fabrication, and installation as well as generating value for the customer at a rate that suits the customer’s needs (e.g., turning a project over in multiple stages versus only one stage). Thus, “Work flow management is facilitated by effective Work Structuring, which divides the work to be done at the ‘natural joints’ revealed by flow analysis, as opposed to the traditional work packages structured to facilitate cost control” (Ballard and Koskela 1998).

## 2.4 – Conclusions

The early examples of civil engineering projects helped demonstrate the applicability of the Work Structuring concept. By reviewing related literature in (1) coordination and collaboration, (2) decomposition of work, (3) production management, and (4) the role of specialty contractors and fabricators, we illustrated how the Work Structuring concept relates to the field of project management. Then, by reviewing related literature in (1) lean production and (2) the Transformation-Flow-Value Generation theory of production, we described how the Work Structuring concept is rooted in lean thinking.

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# CHAPTER 3 – HOLLOW METAL DOOR FRAMES

## 3.1 – Case Study Objectives

### 3.1.1 – Understand Current Work Structuring Practice

Case 1, the Hollow Metal Door Frames case study, investigates how practitioners currently structure work. It employs a Work Structuring perspective to analyze problems encountered during job-site installation. As our first test of the Work Structuring concept, Case 1 studies the combination of made to stock (MTS) and fabricated to order (FTO) products to form a simple room enclosure system. This simplicity allowed us to quickly understand the conditions that led to installation problems and then to spend more time investigating reasons for inefficiency and formulating ideas for restructuring work.

### 3.1.2 – Develop Methodology for Work Structuring Practice

Case 1 experiments with techniques for Work Structuring practice. First, we map contractual relationships and work flow to illustrate the relationship between value generation and the structure of supply chains. Then, we try out a manufacturing technique for uncovering alternative Work Structures. For the most promising options, we explore how to characterize the difference between alternative Work Structures, and we investigate the barriers for identifying and implementing these alternatives. Finally, we consider the role of government agencies and trade organizations in Work Structuring. We also reflect on the relationship between variation in design and execution reliability.

## 3.2 – Company and Project Background

The Oscar J. Boldt Construction Company of Appleton, Wisconsin, joined the Lean Construction Institute (LCI) of Ketchum, Idaho, in October 1999 (Boldt 2002). Founded in 1889, Boldt is "a fourth generation, family-owned construction firm" that ranks No. 109 on Engineering News-Record's 2001 list of Top 400 Contractors (Boldt 2005, ENR 2002). Founded in August 1997, LCI is a non-profit research organization devoted to developing "knowledge regarding project based production management in the design, engineering, and construction of capital facilities" (LCI 2005).

To help Boldt's efforts in creating a lean enterprise (Boldt 2002), Greg Howell, Director of LCI, met with Paul Reiser, then Manager of Project Controls (now Vice President of Production and Process Innovation), of Boldt to discuss operations suitable for a First Run Study (Ballard and Howell 1994).

Due to its heavy labor requirements, Mr. Reiser identified the grouting procedure for prison cell door frames on one of its projects as a candidate for a First Run Study. However, as aspects of the grouting procedure got unraveled, it became apparent that problems were actually rooted in Work Structuring. As a result, Boldt's First Run Study became a case study in Work Structuring instead. Then, at the invitation of LCI, we conducted the Hollow Metal Door Frames case study in February 2000.

The Hollow Metal Door Frames case study (i.e., Case 1) focuses on the construction of the Redgranite Correctional Institution in Redgranite, Wisconsin. The project consists of 2 housing buildings that cover a total of 15,310 $m^2$ (164,800 $ft^2$). Most inmate cells were 2.1 m (6’-10”) x 3.8 m or 3.6 m (12’-6” or 11’-8”) in size (Figure 13). Additional facilities cover another 11,140 $m^2$ (119,900 $ft^2$). The 2-story housing buildings contain walls made of precast concrete. The first-level floors are slab-on-grade while the second-level floors are precast concrete slabs. The product design specified that 538 door frames be filled with a 13.8 MPa (2,000 psi) grout mix (Figure 14). Figure 15 illustrates the interface between doorjambs and precast walls, and Figure 16 illustrates the interface between heads and precast walls.

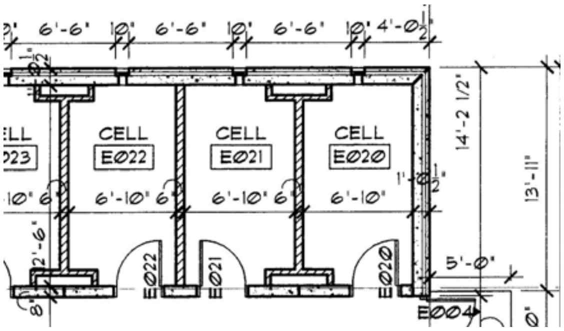

Figure 13: Plan View of Inmate Cells
(Redgranite 1999, Drawings Sheet A-1)

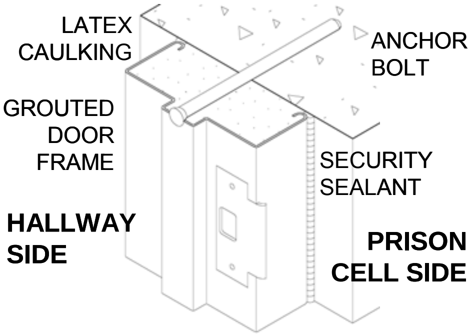

Figure 14: Door Frame against Precast Wall
(image by Padgett 2003)

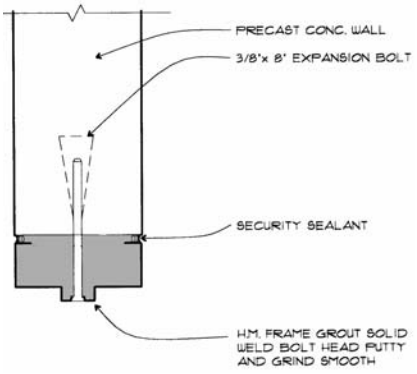

Figure 15: Doorjambs and Walls Interface
(Redgranite 1999, Specifications p. 28.103)

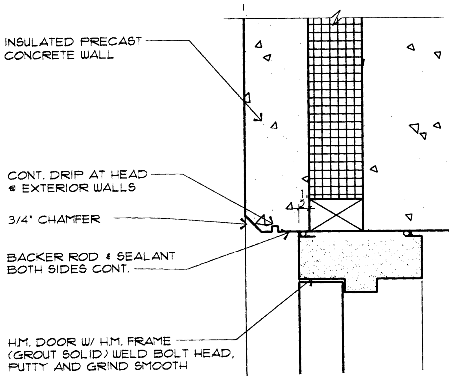

Figure 16: Heads and Walls Interface
(Redgranite 1999, Specifications p. 23.1030)

## 3.3 – Data Collection

Mr. Howell visited Redgranite during construction and took pictures of door frame grouting. Then, we conducted telephone interviews with Boldt and related fabricators to learn about supply and construction for correctional facilities in general. Boldt also forwarded to us a set of project drawings and specifications to assist us in our analysis. We conducted telephone interviews with architects, government agencies, and trade organizations to learn about planning and design for correctional facilities. Towards the end of our study, at the invitation of Boldt, we visited Redgranite in December 2000 to conduct a cost analysis of the alternative Work Structures developed in Case 1.

## 3.4 – Corrections Industry Background

### 3.4.1 – Introduction

Because correctional institutions have security concerns, they require solid door frames. Solid door frames add to security by (1) protecting anchor bolts that connect frames to walls, (2) providing a bond between the frame and wall while also making the frame heavier should an inmate try to push it out, (3) preventing inmates from hiding objects in a hollow frame, and (4) making it more difficult to disable electrical lock mechanisms inside frames. In Case 1, specifications called for hollow metal door frames filled with grout – a common way to design solid door frames for correctional institutions.

We will examine how project participants executed this Work Structure and compare it to alternative Work Structures to determine which option is more efficient in managing transformation of inputs into outputs, maintaining continuous work flow, and generating value (Koskela 2000).

### 3.4.2 – Supply Chain and Contractual Relationships

The Department of Corrections of the State of Wisconsin is the owner of the Redgranite project. The State awarded Boldt a design-build contract for the project based on a guaranteed maximum price of $48 million. Before Redgranite, Boldt had already built 4 prisons in a similar fashion. As design-builder, Boldt took on construction management responsibilities and hired Venture Architects of Milwaukee, Wisconsin, to be project architect. Boldt selected Spancrete Industries, Inc. of Waukesha, Wisconsin, to supply precast walls and LaForce, Inc. of Green Bay, Wisconsin, to supply doors and door frames. Boldt hired Central City Construction, Inc. of Milwaukee, Wisconsin, to install walls and R.J. Jacques of Green Bay, Wisconsin, to caulk door frames. Then, Boldt decided to self-perform the installation and grouting of door frames. Construction at Redgranite began in February 1999 and finished in November 2000.

Figure 17 illustrates key supply and contractual relationships on Redgranite using elements of Rother and Shook's (1998) technique for mapping value streams.

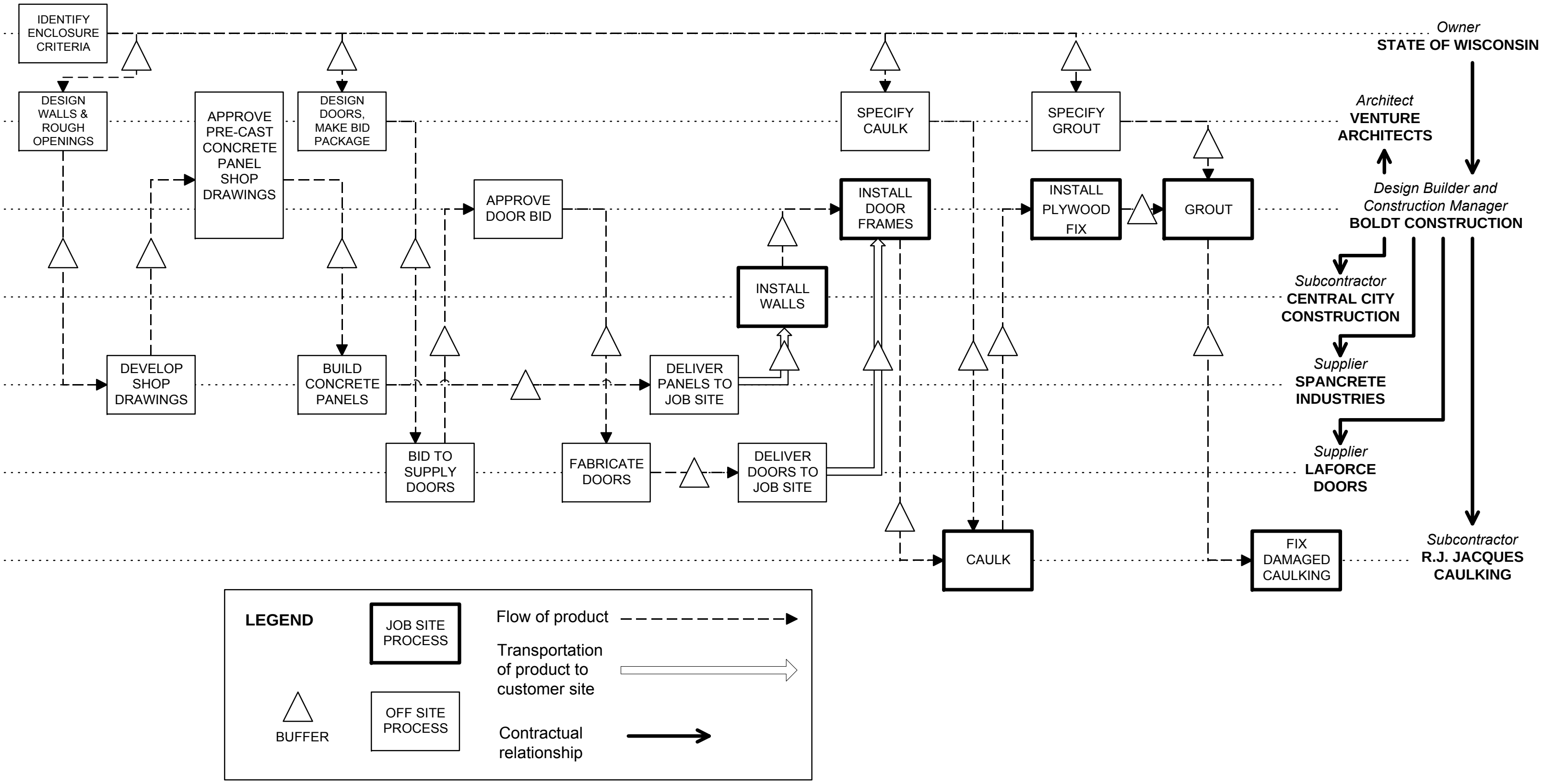

Figure 17: Supply and Contractual Relationships on Redgranite Correctional Institution

### 3.4.3 – Flows of Information

The Work Structure components of Redgranite's cell enclosure system are precast concrete walls, hollow metal door frames, latex caulking, security sealant, and grout.

The flows of information for precast walls design development was as follows. First, the State determined its enclosure criteria. With that information, Venture developed rough openings for door frames and windows. Using this initial design, Spancrete developed shop drawings for approximately 3,000 precast concrete pieces and submitted them to Boldt. After Venture and Boldt reviewed and approved the shop drawings, they gave permission to Spancrete to begin fabrication.

On Redgranite, Venture specified wall sizes even though they did not have details ready for mechanical requirements (e.g., location of louvers, air intake ducts, and exhaust ducts). As a result, when Venture finally completed the mechanical details, several mechanical openings had to be cut on the job-site to accommodate the revised design. Cutting concrete on the job-site is an expensive and time-consuming process. Thus, to keep this problem from reoccurring, Boldt asked Spancrete to install additional sleeves into their walls on the next corrections project in anticipation of mechanical design changes. This strategy worked well because it is easier to fill in extra holes within a concrete wall than to cut out new holes.

The flows of information for door frame specifications development was as follows. With the State's enclosure criteria, Venture developed the door bid package that specified Ceco brand doors and frames 5 months after Spancrete submitted precast wall shop drawings. As a licensed fabricator of Ceco brand products, LaForce submitted a bid to supply doors and frames for Redgranite. Boldt approved LaForce's bid and gave permission to LaForce to proceed with order processing. Then, LaForce delivered products directly to the job-site. From shop drawings to site delivery, procurement took approximately 6 weeks for doors and frames and 10 to 12 weeks for door hardware.

Initially, Venture specified that security sealant be used along both sides of door frames. However, in response to a later request by Boldt, Venture allowed for two kinds of caulking: security sealant on the inside of inmate cells and latex caulking on the outside adjacent to hallways. Bathrooms and kitchens typically use latex caulking. It is not used inside prison cells because inmates may attempt to (1) remove the caulking to store items in a void they create after scraping the caulking away or (2) eat the caulking – latex caulking contains ethylene glycol and eating large amounts of it can result in serious illness or even death (USDHHS 1997). Security sealant is about 55 MPa (8,000 psi) in strength, so it is better at resisting inmate tampering in comparison to latex caulking.

Venture specified a grout that was at least 14 MPa (2,000 psi) in strength and allowed Boldt to develop the mix ratio since Boldt assumed responsibility for grouting frames.

## 3.4.4 – Flows of Goods

### 3.4.4.1 – Installation of Door Frames

Spancrete developed wooden forms for precast wall pours. They added reinforcing bar and wire meshing to help strengthen the walls. Then, after the walls were complete, Spancrete delivered them to the job-site. The lead time from receipt of shop drawings from Spancrete to site delivery of the walls was 12 weeks.

Boldt's installation procedure was the following. First, a worker moved a frame into the cell and propped it against a wall close to the opening (Figure 18). He used a level to draw a plumb line along the door opening to mark where the frame should be installed (Figure 19). Then, he positioned the frame into the door space and lined it up against the plumb line. He aligned and squared the frame with the help of a level and wooden shims (Figure 20). While holding the frame in position, he drilled holes into the frame, installed anchor bolts (Figure 21), and partially tightened them. The worker then added more wooden shims to ensure that the frame was square and plumb before tightening the bolts completely. Finally, he ground the heads of the bolts down, applied Bondo over the bolt heads, and sanded the patch of Bondo to create a smooth finish that matched the door frames finish.

*Figure 18: Door Frame Leaning against Wall*

*Figure 19: Drawing a Plumb Line*

*Figure 20: Inserting Wooden Shims*

*Figure 21: Drilling for Anchor Bolts*

Once the frame was installed, the next step was to caulk the gap between the frame and precast concrete wall. Jacques' procedure was the following. First, a worker cut the shims off with a hand chisel, a procedure called "trim out", so the shim would not protrude through the caulking surface (Figure 22). Then, he inspected the gap between the frame and wall to see if the caulking would stay in place. If the gap was too wide, the worker inserted a foam backer rod (Figure 23). After jamming the backer rod into the crevice, the worker caulked directly over it. On occasion, the backer rod fell into the frame channel. When that happened, the worker installed another backer rod in its place. The worker usually caulked along the doorjambs and then ran the caulking along the head (Figure 24). Finally, he brushed the caulking in a procedure known as "feathering" (Figure 25).

Boldt developed the grout mix by means of trial and error. The grouting crew developed an initial mix, tested it, and found that it did not pump well into the frame because it contained too much aggregate. After consulting two other contractors who had performed similar work, they tried 4 other mixes until they found a good ratio of sand, cement, and water. Boldt decided that this mix was adequate, informed Venture of their mix design, and proceeded to use it on Redgranite.

*Figure 22: Trimming Out*

*Figure 23: Installing a Foam Backer Rod*

*Figure 24: Caulking along the Head*

*Figure 25: Feathering*

With the door frames in place and caulked, workers inserted grout through 2 to 4 holes in the frame called 'grout ports.' Door frame grouting was then broken up into 3 stages: (1) the bottom-half of doorjambs, (2) the top-half of doorjambs, and finally (3) the heads of door frames. Unfortunately, there was a problem with this installation process – pump pressure combined with the wet grout’s hydrostatic pressure caused grout to leak through cracks between the frame and wall, blowing out both backer rods and caulking. Thus, Boldt’s carpenters responded to this problem by introducing a ‘Plywood Fix.’

### 3.4.4.2 – Installation of Plywood Fix

Since frames were already installed at the time of grouting, any leak prevention system had to be applied to the outside of frames. As mentioned earlier, Venture’s initial design called for security sealant on both sides of door frames. However, at the beginning of the project, Jacques had difficulty applying security sealant. This difficulty might have been another factor in the blowout problem. To prevent blowout, workers developed a ‘Plywood Fix’ to help keep the security sealant in place during grouting. They cut two large U-shaped pieces of plywood (sized slightly larger than the frames) and fit each piece directly against the caulked frame. They built C-clamps out of plywood and used them to hold the two U-shaped pieces in. Then, workers added wooden shims between the C-clamps and the U-shaped pieces to tighten the fit (Figure 26 and Figure 27).

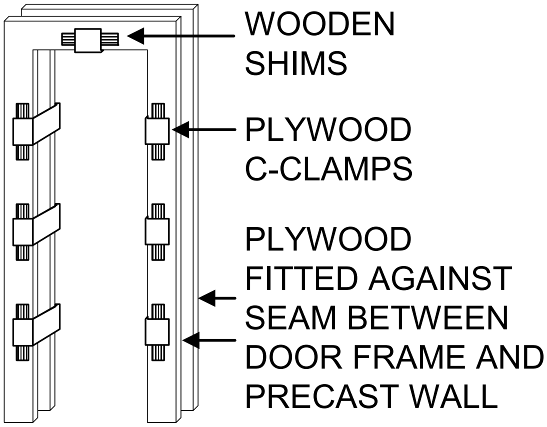

*Figure 26: Diagram of Plywood Fix*

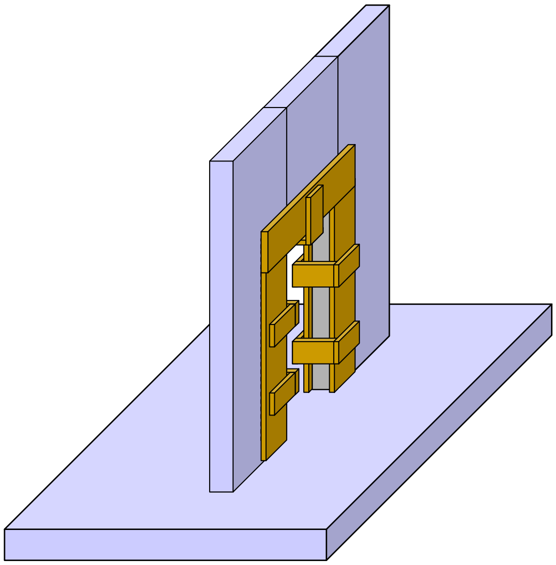

*Figure 27: Plywood Fix Installed*

After pumping in grout and allowing it to set, they removed this fix. Sometimes, the plywood damaged the caulking, so the workers had to re-caulk frames. However, after developing experience in applying the Plywood Fix, the workers figured out how to remove it without damaging caulking. As a result, Jacques did not have to come back and re-caulk everywhere. Boldt's carpenters took about 20 minutes to install the Plywood Fix and 5 minutes to remove it. Figure 17 outlines the Work Structure using the Plywood Fix.

As mentioned earlier, security sealant is more resilient than latex caulking because it is stronger and adheres to surfaces better, but these properties also contribute to a longer and more difficult installation process. In addition, security sealant is more expensive to procure. Thus, Boldt requested that security sealant be used only on the inside edge of door frames and latex caulking be used on the outside because: (1) they had difficulties applying security sealant earlier in the project, (2) it cost more to procure and install security sealant, and (3) they now had a Plywood Fix in place. Venture approved Boldt's request, so they used latex caulking, security sealant, and the Plywood Fix on the first 284 door frames. However, Jacques eventually figured out how to apply security sealant so that it alone kept grout from blowing out. Then, the project stopped using the Plywood Fix and instead used security sealant on both sides of the remaining 254 door frames.

## 3.5 – Improving Product-Process Design Integration

To improve product-process integration, we use the “5 WHYs” manufacturing technique of problem solving (Ohno 1988, Barker et al. 1999 and 2000) to develop a range of ‘fixes’ to the current system. ‘Fixes’ transform existing Work Structures into alternative Work Structures. The 5 WHYs is an integral part of the Toyota Production System (e.g., Shimbum 1995). Ohno (1988) noted, “the Toyota production system has been built on the practice and evolution of this scientific approach (i.e., the 5 WHYs)… [to] get to the real cause of the problem, which is often hidden behind more obvious symptoms.”

When a problem occurs, a worker should ask, “Why did this problem develop?” After coming up with an explanation, the worker should ask again “Why is that the case?” The worker should continue with this repetitive inquiry until at least 5 “Why?”s have been asked and answered. The answer to the last “Why?” gives insight into the root cause of the problem and can reveal methods for improving performance at the systems-level. Then, the strategy for fixing problems is to eliminate root causes by implementing more global changes (Koskela 1992, p. 24-25). On this project, the 5 WHYs helps us understand why the door frame installation process was structured as it was and why it ran into the problems it had. Each of the following sections begins with a discussion of the "Why?". Then, individual fixes that address the question are explained in detail.

## 3.5.1 – Why did caulking and backer rods blow out?

Caulking and backer rods blew out because of the hydrostatic pressure developed by wet grout during the grouting process.

### 3.5.1.1 – Grout Pump Fix

On Redgranite, Boldt had been using an air-pressure powered grout pump operating at 30 MPa (4,350 psi) (Swanlund 2001). Instead, the Grout Pump Fix recommends using a hand-powered grout pump operating at 5 MPa (725 psi), e.g., as supplied by Kenrich (Rountree 2000). These low-pressure pumps are capable of up to 6.1 m (20') of horizontal push and 3.1 m (10') of vertical lift (Kenrich 2002). In particular, the resistance felt while operating a hand-powered grout pump provides a gauge of hydrostatic pressure build-up, so grouters can fill frames quickly without blowing out the grout. As a result, use of a low-pressure grout pump may reduce the number of blowouts.

### 3.5.1.2 – Security Sealant Fix

The Security Sealant Fix is the use of security sealant on both sides of door frames to keep grout from blowing out. We developed the Security Sealant Fix before learning that Boldt successfully implemented it later on the project. As mentioned earlier, halfway through the project, Jacques figured out how to efficiently apply security sealant on both sides of door frames and prevent grout blowout. Therefore, Boldt's request to change the caulking requirements could have contributed to the need for a ‘Plywood Fix’. Also, the cost of applying the Plywood Fix might have negated any materials cost savings attained from using latex caulking instead of security sealant.

### 3.5.1.3 – Pre-mixed Grout Fix

Boldt developed an adequate grout mix by testing 4 to 5 trial mixes. In the process of creating a hand mix that would be liquid enough to fill the entire frame, they may have created one that was too liquid and thus introduced the hydrostatic pressure that caused the caulking blowout. Given the repetitive nature of grouting and since Boldt was involved in other prison projects, they could have conducted a more detailed First Run Study (Ballard and Howell 1994) to develop a better mix.

However, Boldt’s decision to hand mix the grout introduces additional problems. Boldt developed the grout mix of sand, cement, and water on the job-site. When grout is mixed by hand, it is hard to control the proportions. Also, it is difficult to develop a consistent mix since sand can be fine, coarse, wet, damp, or dry.

As an alternative, Boldt can use a pre-mixed non-shrink grout supplied by companies such as 5-Star. Pre-mixed grout has a lower percentage of shrinkage in comparison to hand mixes. Consequently, hand mixed grout has more hollow spots than pre-mixed grout. Another benefit of pre-mixed grout is that it can yield up to 55.2 MPa (8,000 psi) in strength, easily exceeding Venture’s specification of 13.8 MPa (2,000 psi). In contrast, hand mixed grout has difficulty achieving 13.8 MPa (2,000 psi) in strength. Pre-mixed non-shrink grout costs about $45 per 45.4 kg (100-lb) bag, so it is more expensive than hand mixed grout in terms of materials cost. However, using pre-mixed non-shrink grout saves labor costs as pre-mixed non-shrink grout only requires the addition of a specified amount of water. In addition, it can provide greater value by generating a product of consistent quality and meeting or exceeding Venture's strength specifications.

#### 3.5.1.4 – Foam Fix

Boldt might consider using a filler material that develops less pressure, such as a foamed concrete that can achieve over 17.2 MPa (2,500 psi) in strength (Allied 2005). We had also considered spray polyurethane foam (SPF) which is used for roofing, insulation, and climate control applications (SPFA 2005), however SPF might only achieve a strength of 685 kPa (99.3 psi) at best (BASF 2005). Thus, while exploring alternative filler materials, we should investigate the reasoning behind the 14 MPa (2,000 psi) strength requirement for the filler and possible other, implied requirements of the filler.

#### 3.5.1.5 – Hydrostatic Pressure Fix

Currently, Boldt splits the grouting process into 3 stages. They could split grouting into 4 stages by filling doorjambs in 3 stages before filling the head. This would control the magnitude of hydrostatic pressure by limiting the height of the wet grout column.

### 3.5.2 – Why did grout leak through cracks?

Grout leaked through the cracks because of the pump pressure and thin grout mixture. With those two factors, the cracks were not tight enough to hold back grout. This lack of tightness is the reason why backer rods were introduced to provide support when caulking over wide cracks. Since backer rods and caulking combined could not hold back the grout, the carpenters introduced the Plywood Fix.

### 3.5.2.1 – Bungee Cord Fix

Hydrostatic pressure is an issue only along doorjambs since grout is unlikely to blow out along the head due to its limited height. A Bungee Cord Fix could be introduced to prevent blowout along doorjambs. Workers first place a 5 cm x 10 cm (2” x 4”) wood member and a 10 cm x 10 cm (4” x 4”) wood member vertically against each doorjamb (Figure 28). Weather stripping between wood members and door frames helps seal the cracks. Workers would then arrange four 5 cm x 10 cm (2” x 4”) wood members with the help of screws and wing nuts between the vertical wood members and stretch a bungee cord or spring where the upper two and the lower two members come together. As the combined length of the upper two (and lower two) members exceeds the width of the doorway, the wood members would naturally fold outwards. The bungee cord or spring would then pull the members towards each other to create lateral pressure between the vertical members and the precast wall, thereby keeping the fix tightly in place and preventing grout blowout.

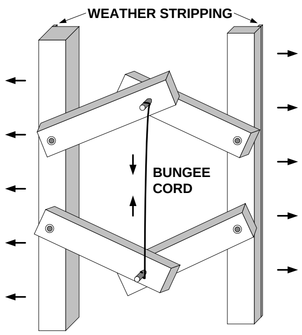

*Figure 28: Bungee Cord Fix*

### 3.5.2.2 – On-site Weather Stripping Fix

Boldt can attempt to tighten the seal between the door frame and precast wall. Before door frame installation, workers have access to the inside of door frames. As a result, they can apply a barrier to the inside without compromising the appearance of the door on the outside. For example, weather stripping might be glued to run along the outside edges of the frame prior to installation. Then, when workers tightened anchor bolts, the weather stripping would be compressed, thereby providing a tight seal. Security sealant would still have to be applied to the inside edge of the frame to prevent tampering by inmates, however the need for latex caulking along the outside edge may be eliminated.

### 3.5.2.3 – Off-site Weather Stripping Fix

Alternatively, the door supplier could be asked to install weather stripping off site. At first, one may not think that hollow metal door fabricators would work with non-metal materials (e.g., weather stripping) or that they would agree to alter a standard design to accommodate a specific project’s needs. This impression results from the long standing separation of trades and the materials each trade has worked with historically, but traditions are changing. For instance, carpenters who traditionally have built frame structures out of wooden studs are today working with metal studs just the same. Thus, the door suppliers might welcome the challenge of adding weather stripping to support the grouting process. Then, they would have a new role as a partner in value generation instead of being just another supplier of commodities.

### 3.5.2.4 – Uneven Leg Channel Fix

Hellmuth, Obata + Kassabaum, Inc. (HOK) has been designing the enclosure system of prison walls and door frames for many years. Based on their experience, they prefer to manage the interface with the use of an Uneven Leg Channel Fix (Isom 2000). The Uneven Leg Channel Fix is not aesthetically pleasing, but it functions extremely well. Once the precast concrete wall has been installed, the worker attaches a 12-gauge steel unequal leg channel (Figure 29). With the channel in place, the worker places an unequal leg door frame against the channel. After leveling and squaring the frame, the worker then welds it into place. Then, the worker runs security caulking along the seams to prevent grout blowout. Although this system is more expensive to procure and install, it is very effective in preventing grout blowout.

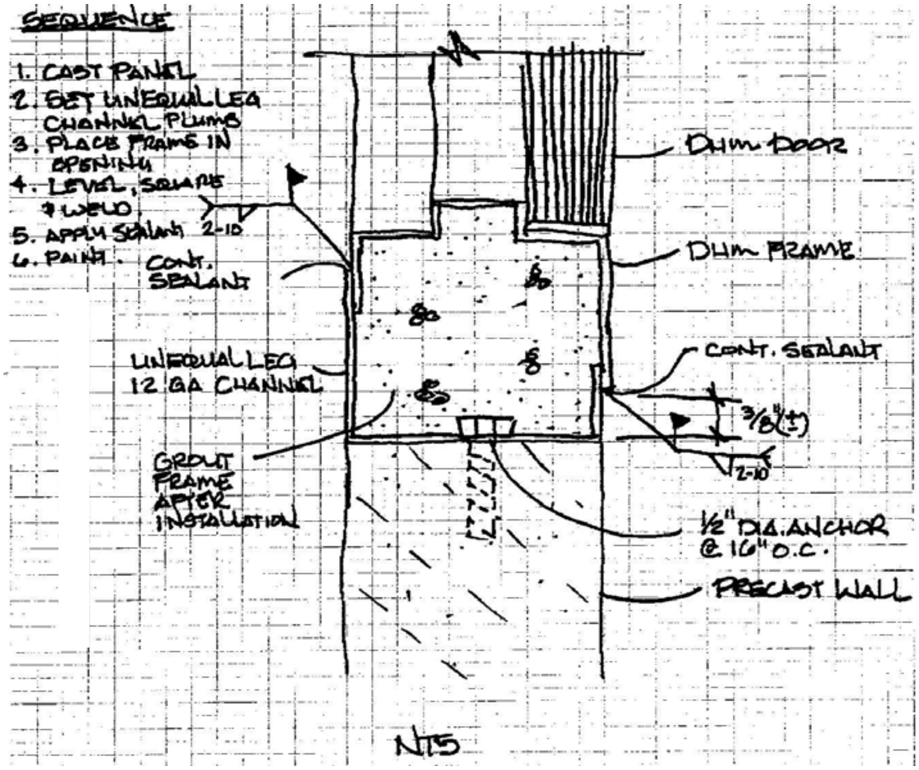

*Figure 29: Uneven Leg Channel Fix (image by Isom 2000)*

## 3.5.3 – Why was grouting of door frames needed?

We do not know the origin of the grouting requirement but speculate that grout adds to prison security by restricting inmate access to the inside of door frames and making it difficult for inmates to push the frame out.

### 3.5.3.1 – Solid Frame Fix

The use of a solid, heavy door frame may alleviate some of these security concerns. However, the Solid Frame Fix may also increase the cost of materials, transportation, and handling due to the additional weight. Some contractors, including Boldt, have tried pregrouting door frames while they are laid flat on the floor. They used plywood forms to keep grout from leaking out. Once the grout had set, they removed the plywood forms and then installed the pre-grouted door frames into place. However, Boldt found this approach to be difficult to implement, so they resorted to the previous method of installing door frames into precast walls before grouting.

### 3.5.3.2 – Concrete Lip Fix

Prefabricating walls with a concrete lip that protrudes on the inside of the cell wall can help eliminate the need for grouting (Figure 30). Then, inmates would only see a recessed door and concrete walls, and the lip would block access to the frame completely. The Concrete Lip Fix would not remove the need for caulking. After anchoring the frame against the lip, the contractor would still need to apply aesthetic caulking on the outside, and the inside seam between the concrete lip and the frame should still be caulked with security sealant to prevent inmate access to the seam.

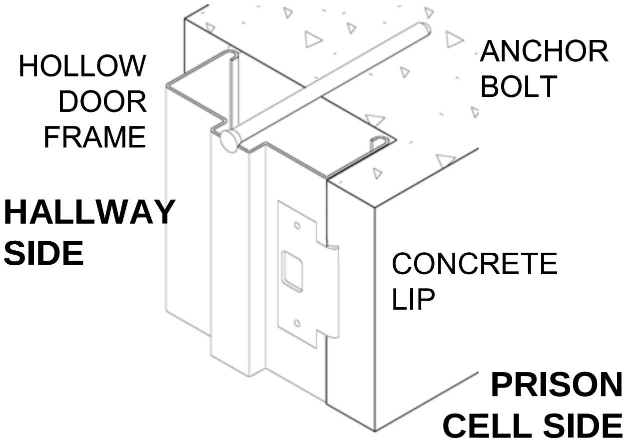

*Figure 30: Concrete Lip Fix (image by Padgett 2003)*

When asked if they could fabricate a concrete lip, Spancrete replied that for a 12.7 cm (5”) thick door frame, walls at least 20.3 cm (8”) thick could accommodate a 7.6 cm (3”) lip (White 2000). A thinner 5.1 cm (2”) lip would not work because it could get damaged during shipping and handling. The addition of a lip would not violate any building codes because that area is not designed to meet any load-bearing requirements. Fabricating a concrete lip requires adding an extra block to wooden forms before pouring walls and adding a piece of reinforcing bar and meshing to strengthen the lip.

#### 3.5.3.3 – Heavy Gauge Steel Door Frame Fix

The need for grouting can also be eliminated by using a door frame made from heavier gauge steel. Then, the frame would be too heavy for an inmate to push out. However, this fix requires that security caulking be strong enough to prevent inmates from tampering with anchor bolts, hiding objects in frames, and disabling electrical lock mechanisms.

HOK has unsuccessfully attempted this fix before (Isom 2000). On one project, they specified a 12-gauge steel door frame in hopes of eliminating the need for grouting. Unfortunately, the accompanying doors were 113.4 to 136.1 kg (250 to 300 lbs) each, making them much heavier than the door frames. As a result, the door frames could not withstand the impact of the heavy doors as they opened and closed. When big chunks of epoxy sealant began popping out and falling onto the floor, HOK asked the contractor to drill holes in the door frames and grout them.

### 3.5.4 – Why were there cracks between frames and walls?

Door frame installers need to have about a 3.2 mm (1/8”) opening between the frame and wall to slide the frame into the wall opening and plumb it properly. This opening will vary in size along the frame due to dimensional tolerances (stochastic variation relative to the design dimensions of a product) during fabrication and placement of the precast walls and metal frames. Openings are to be expected when surfaces touch each other in any assembly of parts since it may be difficult to manufacture each part with a smooth surface as smoothness is a relative concept. In addition, materials change in dimensions over time (e.g., shrinkage cracks, deflection and settlement cracks, and cracks resulting from items that wear out). They also may expand or shrink with temperature changes throughout the day and with the variation in seasons.

The construction industry has developed many kinds of materials and techniques to fill cracks, cover them up, make them water- or air-tight, provide structural integrity to the assembly, or meet other functional requirements.

#### 3.5.4.1 – Field Sequencing Fix

Another means for minimizing hydrostatic pressure is to secure frames while panels are horizontal and grout them before erection. In fact, this work could even be done off site, at the precast wall fabricator’s facilities. Spancrete would thus absorb work from an adjacent trade, namely on site work normally done by the door frame installer.

However, this Field Sequencing Fix may have quality issues. Even when individual parts have been manufactured with little dimensional variation, combining those parts can result in additional variation (Milberg and Tommelein 2004). For instance, precast panels will not be perfectly plumb after erection, and floor slabs will not be perfectly level after erection or pouring. Work Structuring then considers, "To what extent is it worth spending additional resources to remove such variation?" and "How will variation be absorbed or compensated for by the materials and methods applied at a later stage?" If a wall is not plumb, then a frame pre-aligned with it will not be plumb either, thus preventing the door from opening properly. A similar problem arises when the floor is not level. A cost/benefit analysis must accompany the study of alternatives, e.g., paying extra to build ultra flat concrete floor slabs has proven to pay off in many situations.

#### 3.5.4.2 – Tolerance Fix

Tolerances are specified by contract and represent acceptable variation. Nevertheless, if not specified or managed properly, they may compound problems as design and construction progress. Variation not only in production rates (Tommelein et al. 1999) but also in geometry (Milberg and Tommelein 2003) has detrimental impact on those downstream in the supply chain.

On Redgranite, Venture developed design drawings that showed rough openings in precast walls. Spancrete developed shop drawings based on these rough openings. The recommended tolerance for openings in precast walls is 0.64 cm (1/4") (Freedman 1996, p. 162). Because Spancrete builds walls within a tolerance of 0.32 cm (1/8") and due to field installation requirements of a 3.2 mm (1/8") opening between the frame and wall, Spancrete increases the dimensions given by Venture by 0.64 cm (1/4”) on each side of the door opening so that the door opening is 0.64 cm (1/4”) taller and 1.27 cm (1/2”) wider than Venture’s design. Then, once Boldt and Venture approved Spancrete’s shop drawings, they proceeded with wall fabrication (Figure 17).

Five months after Spancrete’s shop drawings were approved, Venture developed the bid package that specified door frames. LaForce submitted a bid to supply the frames using the door openings shown in Venture’s initial design drawings and door bid package. LaForce builds frames within a tolerance of 0.08 cm (1/32”). A door specified as 92 cm (3’) wide to be used in a door frame that is 5.1 cm (2”) thick on each side is built with a matching frame width of 101.6 cm (3’-4”). Spancrete’s corresponding door opening would then be 102.9 cm (3’-4-1/2”) wide, leaving an average horizontal gap of 1.3 cm (1/2”) (Figure 31).

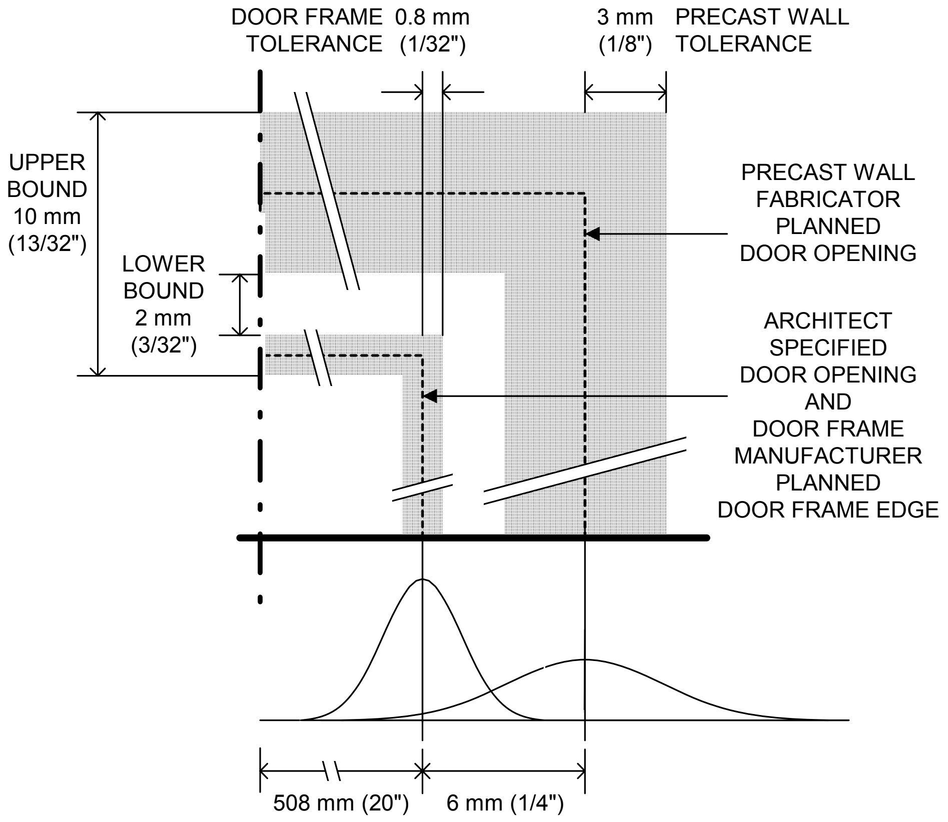

*Figure 31: Tolerances on Door Frame and Precast Wall*

Poor quality in design and construction results in frames not fitting in the wall opening or leaving an excessively wide gap. Both situations occurred on Redgranite. Sometimes, door openings had to be widened by grinding down the concrete for the frame to fit. Other times, masonry in-fill had to be used to bridge an opening that was too large. This uncertainty made it difficult for Boldt to anticipate which door frame installations required the Plywood Fix. As a result, they installed the Plywood Fix on all frames because doing so was easier than judging which caulking jobs would hold up against grouting and then dealing with random blowouts later.

Considering these tolerances, the computed range in dimensions for the opening between the wall and the frame are:

- lower bound = (mean $value_{wall}$ - $tolerance_{wall}$) - (mean $value_{frame}$ + $tolerance_{frame}$)

  = 2.4 mm (3/32”)

- upper bound = (mean $value_{wall}$ + $tolerance_{wall}$) - (mean $value_{frame}$ - $tolerance_{frame}$)

  = 10.3 mm (13/32”)

These numbers assume that the frame is perfectly centered in the door opening. If not, the lower bound may be 0 and the upper bound up to twice as large. Note also that the tolerance range may be exceeded on occasion, which is why Figure 31 shows bell curves (normal distributions) to depict the range of variation. Consequently, some frames and walls may not fit together at all, but swapping them out may result in a fit.

### 3.5.5 – Why are frames and walls made separately?

These two components are made separately because they require different materials, knowledge, skills, and fabrication tools. Industry specialization has further led to this division of labor. Much of the way work is done is governed by this fragmentation. It will come as no surprise that through such fragmentation, project participants lose valuable opportunities for integrating product and process design.

#### 3.5.5.1 – Precast Fix

Taking the Concrete Lip Fix one step further, why not cast frames directly into walls, i.e., use frames as a part of precast formwork? The Precast Fix thus involves casting door frames directly into precast walls, which are made from a 35 MPa (5,000 psi) concrete. It requires that (1) LaForce delivers frames to Spancrete’s facilities, (2) Spancrete casts frames into walls and delivers assemblies to the job-site, and (3) Central City installs the assemblies into place. If they are unable to use the Uneven Leg Channel Fix, HOK will try to use the Precast Fix to manage the interface between frames and walls (Isom 2000).

The Precast Fix requires that door frames be procured in advance and delivered in time for the pouring of precast walls. The successful implementation of the Precast Fix depends on Spancrete casting frames in the same plane as walls and Central City installing the assemblies plumb onto the concrete floor slabs. Spancrete also needs to determine how to make the Precast Fix work on levels with precast, pre-stressed hollow core floor slabs that are thin and would not allow the same wall installation flexibility as levels with a slab on grade. Furthermore, Spancrete is concerned about receiving, handling, and shipping liabilities: without additional compensation, they do not want to be held responsible for door frames damaged by other parties.

#### 3.5.5.2 – Module Fix

The Module Fix moves work off-site. Companies such as Oldcastle Rotondo of Rehoboth, Massachusetts, Tindall Corporation of Petersburg, Virginia, and Rotondo Weirich of Lederach, Pennsylvania, fabricate single-cell and 2-cell prison modules. These modules consist of 5 or 6 sides and come with door and window frames cast-in-place as well as utilities and furniture already installed. The Module Fix radically changes the process of building prisons as the contractor purchases completed prison cells and then lifts them into place. This entails higher materials procurement costs and different on-site skill and equipment needs, but it reduces labor risks and associated costs. It also improves quality consistency since modules are fabricated in a controlled environment.

## 3.6 – Work Structuring Analysis

### 3.6.1 – Impact of Fixes

Table 5 uses a Work Structuring perspective to illustrate how each fix manages product-process design integration. Then, it details each fixes' impact on cell enclosure system performance in relation to the Plywood Fix. From Table 5, we see that fixes that respond to earlier 5 WHYs questions primarily improve schedule performance, whereas fixes that respond to later 5 WHYs questions generate mixed results in terms of impact on cell enclosure system performance.

Although this analysis is subjective, it can be used as a common platform for project participants to discuss their experience on past projects and perception on the differences between alternatives. Then, they can identify the most promising alternative Work Structures for further consideration.

### 3.6.2 – Implementation of Fixes

A Fix-Implementation Table notes which project participants are involved in the implementation of each fix (Table 6). Very few fixes are local, that is, very few are under the control of a single project participant. Also, all project participants are involved in at least one fix.

*Table 5: Product-Process Design Integration by Fixes (“Δ” = Changes, “+” = Positive Impact, “–” = Negative Impact)*

| FIXES | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| Grout Pump Fix | Δ | | | + | + | | + | + |
| Security Sealant Fix | | | Δ | Δ | | + | + | |
| Pre-mixed Grout Fix | Δ | Δ | | Δ | | + | + | – |
| Foam Fix | Δ | Δ | | Δ | | | + | |
| Hydrostatic Pressure Fix | | | Δ | | + | | – | – |
| Bungee Cord Fix | | | Δ | Δ | | | + | |
| On-site Weather Stripping Fix | | Δ | Δ | | | | + | |
| Off-site Weather Stripping Fix | Δ | Δ | | | | | + | |
| Uneven Leg Channel Fix | Δ | Δ | Δ | Δ | + | + | – | – |
| Solid Frame Fix | | | Δ | Δ | – | | – | – |
| Concrete Lip Fix | | Δ | Δ | | + | + | – | – |
| Heavy Gauge Steel Frame Fix | Δ | Δ | Δ | Δ | – | + | – | – |
| Field Sequencing Fix | | | Δ | Δ | + | – | + | |
| Tolerance Fix | | + | | Δ | | + | – | – |
| Precast Fix | Δ | Δ | Δ | Δ | + | + | + | + |
| Module Fix | Δ | Δ | Δ | Δ | + | + | + | – |

*Table 6: Project Participant Involvement in Implementation of Fixes*

■ perform fix ▦ work affected by fix ▤ approve fix

| GOAL | FIXES | Venture Architects | Boldt Construction | Spancrete Industries | LaForce Doors | Central City Wall Erection | Jacques Caulking |
|---|---|---|---|---|---|---|---|
| **Prevent Caulking Blowout** | Grout Pump Fix | | ■ | | | | |
| | Security Sealant Fix | ▤ | ▤ | | | | ■ |
| | Pre-mixed Grout Fix | ▤ | ■ | | | | |
| | Foam Fix | ▤ | ■ | | | | |
| | Hydrostatic Pressure Fix | | ■ | | | | |
| **Prevent Grout Leakage** | Plywood Fix (Actual Fix) | | ■ | | | | ▦ |
| | Bungee Cord Fix | | ■ | | | | |
| | On-site Weather Stripping Fix | | ■ | | | | |
| | Off-site Weather Stripping Fix | | ▤ | | ■ | | |
| | Uneven Leg Channel Fix | ▤ | ■ | | ■ | | |
| **Eliminate Grouting** | Solid Frame Fix | ▤ | ▦ | | ■ | | |
| | Concrete Lip Fix | ▤ | ▦ | ■ | | | |
| | Heavy Gauge Steel Frame Fix | ▤ | ▦ | | ■ | | |
| **Manage Cracks** | Field Sequencing Fix | ▤ | ■ | | ▦ | ▦ | ▦ |
| | Tolerance Fix | | ▦ | ■ | ■ | | |
| **Combine Components** | Precast Fix | ▤ | ▦ | ■ | ▦ | ▦ | ▦ |
| | Module Fix | ▤ | ▦ | ▦ | ▦ | ▦ | ▦ |

When we outlined these fixes to Boldt in December 2000, Boldt noted that they had figured out how to successfully implement the Security Sealant Fix on the second half of Redgranite's doors. As a result, Boldt removed the Foam Fix, Hydrostatic Pressure Fix, Bungee Cord Fix, On-site Weather Stripping Fix, Off-site Weather Stripping Fix, Field Sequencing Fix, and Tolerance Fix from further consideration.

For their next project, Boldt planned to use the Security Sealant Fix and try the Grout Pump Fix and Pre-mixed Grout Fix because they were relatively inexpensive experiments. If the fixes failed, it would not cost Boldt much to revert back to the original installation approach employed on Redgranite. Boldt also selected the Precast Fix, Heavy Gauge Frame Fix, Solid Frame Fix, Uneven Leg Channel Fix, Concrete Lip Fix, and Module Fix for further study. Table 7 reflects Boldt's classification of fixes.

*Table 7: Boldt's Classification of Fixes*

| **Fixes to be tested on the next project** | **Fixes to be studied further** | **Fixes eliminated from further consideration** |
|---|---|---|
| Security Sealant Fix | Precast Fix | Foam Fix |
| Grout Pump Fix | Heavy Gauge Frame Fix | Hydrostatic Pressure Fix |
| Pre-mixed Grout Fix | Solid Frame Fix | Bungee Cord Fix |
| | Uneven Leg Channel Fix | On-site Weather Stripping Fix |
| | Concrete Lip Fix | Off-site Weather Stripping Fix |
| | Cell Module Fix | Field Sequencing Fix |
| | | Tolerance Fix |

In Spring 2001, Boldt successfully used the Security Sealant Fix and the Grout Pump Fix on a prison project in Taycheedah, Wisconsin. Boldt chose not to try the Pre-mixed Grout Fix because they felt their own hand-mixed grout was sufficient.

### 3.6.3 – From Fixes to Alternative Work Structures

Fixes represent methods for adjusting an existing Work Structure. Project participants should then combine complementary fixes into alternative Work Structures. For example, Boldt’s decision to try the Security Sealant Fix and Grout Pump Fix on Taycheedah represents an alternative Work Structure. This Work Structure achieves the original design intent, so it involves minor changes to the interface between frames and walls. Boldt also identified the Precast Fix as another promising alternative Work Structure since it changes *who* does *what* and *when* for the interface between frames and walls with the promise of considerable improvements in safety, quality, schedule, and budget.

### 3.6.4 – Comparing Alternative Work Structures

Table 8 compares the alternative Work Structures to help Boldt choose a Work Structuring direction for future projects. We used comparison characteristics that help elucidate how each Work Structure transforms inputs into outputs, establishes or maintains continuous work flow, and generates value. However, the comparison characteristics are by no means exhaustive or prescriptive; they simply serve as a starting point for distinguishing the difference between alternative Work Structures.

*Table 8: Comparison of Alternative Work Structures*

| **Alternative Work Structure 1: Security Sealant Fix + Grout Pump Fix** | **Alternative Work Structure 2: Precast Fix** |
|---|---|
| *Project participants that implement the alternative Work Structure* | |
| **Jacques** - Apply security sealant to both sides of door frames.<br>**Boldt** - Use hand-powered grout pump. | **Spancrete** - Cast door frames into precast concrete walls. |
| *Project participants that approve the alternative Work Structure* | |
| No approval required. | **Venture** - Approval required due to replacement of grout with concrete. |
| *Project participants whose work is affected by the alternative Work Structure* | |
| **Kenrich** - Supply the grout pump. | **Boldt -** No longer needs to grout door frames.<br>**LaForce** - Deliver door frames to Spancrete.<br>**Central City** - Precast walls are heavier due to embedded door frames.<br>**Jacques** - No longer needs to apply sealant. |
| *Major handoffs required by project participants before they can execute their work* | |
| **Central City** - Workspace from Boldt and walls from Spancrete to erect walls into place.<br>**Boldt** - Workspace from Central City and door frames from LaForce to install door frames.<br>**Jacques** - Workspace from Boldt to apply sealant.<br>**Boldt** - Workspace from Jacques and grout pump from Kenrich to grout door frames. | **Spancrete** - Door frames from LaForce to fabricate walls.<br>**Central City** - Workspace from Boldt and walls from Spancrete to erect walls containing door frames into place. |
| *Materials handling* | |
| **LaForce** - Deliver door and frames to job-site.<br>**Spancrete** - Deliver walls to job-site.<br>**Kenrich** - Deliver grout pump to job-site. | **LaForce** - Deliver door frames to Spancrete earlier and doors to job-site later.<br>**Spancrete** - Deliver walls + frames to job-site. |
| *Interface tolerance management* | |
| **Jacques** - Foam backer rods and sealant fill cracks between door frames and walls.<br>**Boldt** - Grout fills in cavity between door frames and walls. Frame installer uses shims to get door frames plumb and square. | **Spancrete** - Formwork to hold door frame in place during concrete pour and cure and to control door frame square-ness.<br>**Central City** - Installed walls must be plumb to ensure door frames can open properly. |
| *Safety* | |
| **Boldt** - Hand-powered grout pump does not require electricity or air tools. | **Central City** – Need to lift heavier loads since precast walls contain door frames. |

| | |
|---|---|
| *Influence of worker on product quality* | |
| **LaForce** - Finish quality of doors and frames.<br>**Spancrete** - Finish quality of walls.<br>**Central City** - Plumbness of walls.<br>**Boldt** - Plumbness and squareness of doors and door frames as well as grouting of frames without blowouts.<br>**Jacques** - Finish quality of sealant. | **LaForce** - Finish quality of doors and frames.<br>**Spancrete** - Finish quality of walls (including filling of concrete voids) and initial plumbness and squareness of frames in relation to walls.<br>**Central City** - Final plumbness of walls and frames. |
| *Aesthetics of interface* | |
| **Jacques** - There is a visible line of sealant between the frame and wall.<br>**Boldt** – Need to Bondo and grind 2.5 cm (1.0”) grout ports to produce a clean finish along frames. | **Spancrete** - Wall runs flush against frames. Close up 6.4 mm (0.25”) weep holes to produce a clean finish along frames. |
| *Performance* | |
| **Jacques, Boldt, and Spancrete** - Provide a 55 MPa (8,000 psi) sealant barrier against inmate access to gaps that might exist between the 14 MPa (2,000 psi) grout and 34 MPa (5,000 psi) walls. | **Spancrete** - Provide a 34 MPa (5,000 psi) precast concrete barrier against inmate tampering. |
| *Schedule* | |
| **Boldt** - Eliminates time spent on installing Plywood Fix and rework when grout blows out of door frames.<br>**Jacques** - Increases time spent on applying security sealant. | **Boldt** - Eliminates time spent on installing Plywood Fix, rework when grout blows out of door frames, and grouting.<br>**Jacques** - Eliminates time spent on applying security sealant.<br>**LaForce** - Door frames must be specified, processed, and delivered earlier than usual.<br>**Spancrete** - Increases time spent on receiving, storing, and handling door frames. |
| *Cost* | |
| **Boldt** - Eliminates cost of air pump rental, Plywood Fix, and rework due to grout blowout. Adds cost of hand pump.<br>**Jacques** - Increases labor cost associated with the application of sealant on both sides of door frames. | **Boldt** - Eliminates cost of Plywood Fix and grouting. Increases cost of design change approval, earlier delivery coordination of door frames to Spancrete.<br>**Jacques** - Eliminates cost of security sealant.<br>**Spancrete** - Increases cost to receive, store, and handle door frames.<br>**Central City** - Increases cost to erect heavier walls. |

| | |
|---|---|
| *Liability* | |
| No liability changes. | **Venture** and **Boldt** - Liability may shift since Boldt proposed the design change.<br>**Spancrete** - Liability increases since it must receive and cast door frames into walls.<br>**Central City** - Liability increases since walls will be heavier due to door frames. |
| *Achievement of project participant values* | |
| **Venture** - Design cells that are resistant to inmate tampering. Also, use prison designs that have worked on past projects.<br>**Jacques** - Maximize security sealant work. | **Venture** - Design cells that are resistant to inmate tampering.<br>**Boldt** - Minimize congestion on job-site to reduce risk of accidents. |
| *Supporters of the alternative Work Structure and why* | |
| **Jacques** – Has more work to do.<br>**Kenrich** - They can sell pumps.<br>**Venture** - Product design has proven to be effective on past projects. | **Boldt** - Transfers risks, costs, and time associated with frame handling and installation, grouting, and applying sealant.<br>**Spancrete** – Simplifies forming process for concrete pours. |
| *Opponents of the alternative Work Structure and why* | |
| No obvious opponents. | **Venture** - They have not tested this design before.<br>**Jacques** - Eliminates work. |
| *Execution predictability* | |
| **Boldt** - Grout does not blow out of door frames as often, so grouting process will be more reliable. There can still be a fitting problem for door frames and precast wall door openings. | **Boldt** - Fewer handoffs of work to manage between various project participants due to restructured process. No more fitting problems with door frames and precast wall openings.<br>**Venture** - Door frames need to be specified earlier in design development. |
| *Potential benefits* | |
| **Boldt** - Removes need for Plywood Fix. Experimenting with this alternative Work Structure is inexpensive. If it fails, it is easy to revert back to original design. | **Boldt** - Removes need for Plywood Fix, caulking, and grouting.<br>**Wisconsin Department of Corrections** - Provides a better quality interface between frames and walls. |
| *Potential risks* | |
| **Wisconsin Department of Corrections** - Seam between door frame and precast wall can be tampered with by inmates. | **Boldt** - Testing may or may not convince Venture that this alternative Work Structure meets performance requirements of design.<br>**Central City** - Door frames might not be plumb after precast wall installation, so doors cannot open properly. Although Central City is not responsible for this problem, they may be asked to fix it. |

### 3.6.5 – Implementing Alternative Work Structures

As mentioned, Boldt successfully used the Security Sealant Fix and the Grout Pump Fix on their next prison project. However, Boldt was initially skeptical that a hand-powered grout pump could be capable of grouting hundreds of door frames on a prison project. Nevertheless, once Boldt tried the Grout Pump Fix at Taycheedah, they found that it "worked like a charm" (Swanlund 2001).

Successful implementation of the Precast Fix is more difficult since it requires that (1) Venture specify door frames earlier, (2) Boldt procure door frames earlier from LaForce, clarify liability for damaged frames, and compensate Spancrete for additional handling of door frames, (3) Spancrete cast door frames consistently in the same plane as walls and deliver walls with embedded doors to the job-site, (4) Central City safely lift heavier walls, and (5) Boldt control construction tolerances of the building structure (especially the camber in floor slabs) so that pre-cast door frames will function properly.

Accordingly, Boldt met with Spancrete to discuss the feasibility of implementing the Precast Fix. Spancrete first noted that Boldt and Venture should decide if their priority is to have 'fully encased with concrete' frames or 'mostly encased with concrete' frames. 'Fully encased with concrete' frames are more expensive to fabricate since they require the addition of weep holes. Consequently, 'Mostly encased with concrete' frames will be easier to fabricate and may prove to be sufficient in preventing inmate tampering.

Spancrete then noted that they normally cast an angle iron strongback across door frame openings to protect walls from warping during shipping. Then, at the job-site, a worker cuts off strongbacks with a blowtorch. With a door frame inside the opening, Spancrete will need to develop another method for protecting walls from such warping. Project participant could even ask LaForce if they can modify their door frames to assist with this warping problem. Regardless, Spancrete expressed confidence that they could make the Precast Fix work with a marginal increase in cost, if any.

The State of Wisconsin's use of design-build contracting indicates a willingness to try innovative designs as long as they meet performance criteria. Therefore, the primary challenge in getting approval for implementing an alternative Work Structure that uses the Precast Fix lies with Venture Architects since they carry design liability. Since the Precast Fix replaces grout with stronger concrete, Venture may not object to this fix. However, Venture may require proof (e.g., through testing) that the Precast Fix, like the original design, meets project performance requirements. Regardless of the test outcome, Boldt may need to cover any costs associated with trying to get approval for the fix.

## 3.7 – Lessons Learned

### 3.7.1 – Impact of Fragmentation on Systems

The system studied at Redgranite, comprising precast walls, door frames, caulking, and grout, is about as simple a system can get. Nevertheless, this system was plagued with problems as revealed by the introduction of the Plywood Fix.

To improve system performance, various perspectives should be considered as each project participant has different roles to play. The owner, architect, and fabricators negotiate their resources with owner requirements to develop the product design. The wall erectors, frame installers, caulkers, and grouters negotiate their standard work procedures and the product design to develop operations designs. The construction manager negotiates owner requirements and the sequencing preferences of various project participants to develop the project's overall process design.

Unfortunately, since project participants rarely have the opportunity to consider Work Structuring together and early enough in the process to decide what would work best for the system, they can miss opportunities to improve product and process design integration. Instead, industry fragmentation encourages them to protect their own interests by optimizing their own work as opposed to overall system performance.

Work processes in current practice generally appear to be acceptable, not necessarily because they are optimal—often they are far from it—but rather because they have proven to work. In Case 1 also, the procedure for grouting frames worked on past projects. Productivity improvement studies might have suggested incremental changes (e.g., improving the grouting procedure itself by using different methods and ingredients) but it is doubtful they would have led to radical, global changes (e.g., simplifying the process by eliminating the grouting procedure altogether) because they are operation-centric and rarely if ever cut across organizational boundaries.

### 3.7.2 – Installers as Partners in Innovation

If product designs require interfaces between components that are difficult to build, installers can (1) refuse to deal with the interfaces until they get redesigned (e.g., by redesigning the components or introducing another component to mediate between the components that do not interface well) or (2) work around the design with ingenious solutions. Such workarounds are costly and time consuming, yet they are an accepted way to perform work. In addition, since contracts have already been signed, installers may choose to avoid questioning the design by assuming that work must proceed according to the original product design. Furthermore, installers do not necessarily complain about site problems because (1) contractually speaking, site problems may be considered theirs to resolve, (2) they may have more important problems to address such as developing bargaining tactics and determining which battles to fight, and (3) complaining might reflect poorly on their trade skill and pride ("tricks of the trade") so they believe workarounds are what they are supposed to do.

The Plywood Fix shows how construction workers can apply their craftsmanship skillfully and creatively to solve problems encountered on the job-site. Slaughter (1993) noted that innovations on the job-site are needed because problems at interfaces between products are less likely to be tackled by any one of the product suppliers. In addition, product suppliers may worry that any work they do in terms of interface management could be interpreted as interfering with 'means and methods'—an area normally reserved for installers. Consequently, a lack of constructability consideration and interface management during design forces contractors to employ highly skilled craftsmen to negotiate tricky interfaces between incompatible components. Not only is this expensive; the continued reliance on highly skilled craftsmen in future years is unrealistic as fewer people are entering the construction trades.

It therefore makes sense to consider Work Structuring earlier on a project to negotiate a balance between (1) the capabilities of project participants, (2) product design requirements, (3) interface conditions, and (4) project performance expectations. Accordingly, owners and architects should welcome the increasing number of contractors that are trying to move upstream in the supply chain to become much more involved during design development.

### 3.7.3 – 'Right-Sizing' Resources

Boldt's home office owned the air-powered grout pump and charged $1,200 per month for its use. The Redgranite project had to 'rent' the air-powered grout pump at this rate for 5 months. In contrast, a Kenrich Products hand-powered grout pump costs $475 to purchase, and Kenrich customers usually purchase one new pump for each project that requires door frame grouting (Rountree 2000). On Taycheedah, Boldt grouted about 250 door frames using one hand-powered grout pump, and they were still using the same pump on other grouting projects thereafter. Maintenance-wise, Boldt had to replace a diaphragm on the grout pump once for $20 when it wore out from passing aggregates. Thus, by rightsizing to improve operations, Boldt also saved money in this case.

The Grout Pump Fix argues for 'right-sizing' equipment, rather than assuming that 'bigger is better.' Boldt may have introduced problems by using a pump that was too powerful, perhaps believing that it could enable workers to grout doors faster. Had Boldt used a low-pressure grout pump, the sealant could have held up better against a slowly increasing column of grout. Therefore, Boldt can reduce the waste of using inadequate equipment (Alarcon 1994, p. 371) by implementing changes such as the Grout Pump Fix.

### 3.7.4 – Innovative Environments Foster Breakthroughs

When Spancrete investigated the feasibility of the Precast Fix, they came up with another idea for improving the grouting process. After grouting, Boldt's carpenters typically spend considerable time to Bondo, grind, sand, and paint grout ports to match the frame's metal finish. Spancrete noted that they could introduce grout ports into the precast walls right above door openings. Then, covering and hiding grout ports in concrete would be easier than covering and hiding grouts ports in metal. Thus, should the Precast Fix not be adopted, Boldt at least had another good idea for improving the grouting process.

### 3.7.5 – Perceived vs. Actual Impact of Changes

The Precast Fix appeared to be a radical departure from the original design and allocation of work, so there was concern about its cost of implementation. In particular, project participants had the added task of minimizing camber in floors so that precast walls containing doors could be installed plumb. However, Spancrete believed the Precast Fix had minimal impact on cost since they would not have to worry about the finish surface of door openings. Also, positioning door frames might be completed more quickly than blocking out door openings with wood members, so time saved from faster wall forming could be devoted to receiving and handling frames. Consequently, although the Precast Fix seemed expensive to implement, it could actually save Boldt the cost of grouting, caulking, and applying the Plywood Fix.

Using project information available at the time of our December 2000 cost analysis, we calculated approximate costs associated with the existing Work Structure (Table 9) and benefit-cost ratios associated with selected fixes (Table 10). Since we could not easily distinguish which 14-gauge and 16-gauge steel door frames required grouting, we assumed a 2:1 ratio of 14-gauge doors to 16-gauge doors (Table 11) to determine approximate costs associated with door procurement. Based on our findings, it comes almost as no surprise that Boldt tried and successfully implemented the Grout Pump Fix on their next prison project in Taycheedah, Wisconsin.

*Table 9: Approximate Costs Associated with Existing Work Structure*

| **ITEM** | **COST** |
|---:|---:|
| *Materials cost for 179 16-gauge doors @ $152 each* | *$27,200* |
| *Materials cost for 359 14-gauge doors @ $184 each* | *$66,100* |
| *Plywood Fix implementation* | *$7,800* |
| GROUTING FRAMES: | |
| Materials cost | $14,400 |
| Labor cost | $92,500 |
| Equipment cost | $6,000 |
| *Total cost* | *$112,900* |

*Table 10: Benefit-Cost Ratios Associated with Selected Fixes*

| FIX | COST | ELIMINATES | BENEFIT | B/C RATIO |
|---|---:|---|---:|---:|
| Security Sealant Fix | $3,900 | Plywood Fix ($7,800) | $3,900 | 1.0 |
| Grout Pump Fix | $500 | Plywood Fix ($7,800)<br>Equipment cost for grouting frames ($6,000) | $13,300 | 26.6 |
| Pre-mixed Grout Fix | $8,000 | Materials cost for grouting frames ($14,400) | $6,400 | 0.8 |
| Precast Fix | $10,000 | Total cost for grouting frames ($112,900) | $102,900 | 10.3 |
| Heavy Gauge Steel Frame Fix @ $396 each | $213,000 | Materials cost for door procurement ($93,300)<br>Total cost for grouting frames ($112,900) | ($6,800) | Eliminated from consideration |

## 3.7.6 – 5 WHYs Reveal Global Fixes

The 5 WHYs help project participants transition from developing easy-to-implement local fixes to considering more difficult global fixes. For example, in Case 1, the earlier WHYs represent typical questions by installers who tend to resolve their problems without involving other project participants. In contrast, later WHYs represent strategic planning questions that can drastically alter the envisioned system of frames and walls.

Unfortunately, project participants seldom take the time to ask the 5 WHYs to consider broader Work Structuring issues because of the pressure to begin work. This urgency is based on the flawed logic that “the sooner individual activities begin, the sooner the overall project will finish.” Then, project participants fail to take advantage of the Level of Influence they have during the early stages of a project when schedule pressures encourage them to adopt more conservative designs based on ‘received traditions’ (Schmenner 1993, p. 379). Subsequently, new projects tend to resemble past projects in more ways than designers like to admit.

### 3.7.7 – Impact of Design Variation

At the work process level (i.e., the level at which we analyzed grouting procedures), most work seemed repetitive. However, at the operations level, the door frame installation process was complicated by the use of at least 5 different door sizes. Table 11 outlines the size and gauge of steel variation found within Redgranite's door design. These design variations introduced variability into door frame installation and in precasting work. Specifically, varying door sizes complicated the process of fitting door frames into wall openings while varying gauges required additional effort to sort and handle door frames.

*Table 11: Size and Gauge of Steel Variation of Door Design*

| Size Configuration | Door Width | Door Height | 14-Gauge Steel | 16-Gauge Steel | Total |
|---|---|---|---|---|---|
| A | 2' - 10" | 7' - 0" | 385 | 97 | 482 |
| B | 3' - 0" | 6' - 10" | 16 | 1 | 17 |
| C | 3' - 0" | 7' - 0" | 46 | 59 | 105 |
| D | 3' - 0" | 7' - 2" | 23 | 50 | 73 |
| E | 3' - 0" | 7' - 10" | 4 | 10 | 14 |
|  |  |  | 474 | 217 | 691 |

Project participants should determine if the value generated from these subtle variations in design justify the added complexity in installation. For example, they could consider:

- Are size configurations B and E necessary?
- What is the impact of replacing doors with size configuration D with size configuration C instead, or vice versa?
- What is the cost of replacing all 16-gauge steel doors with 14-gauge steel?

- Is this replacement cost less than the cost associated with sorting and handling 14-gauge vs. 16-gauge steel doors?

The cost of replacing all 16-gauge steel doors with 14-gauge steel is:

- 217 doors * ($184 for 14-gauge steel – $152 for 16-gauge steel) = $6,900.

The cost of purchasing all door frames is:

- 474 doors * ($184 for 14-gauge steel) + 217 doors * ($152 for 16-gauge steel) = $87,200 + $33,000 = $120,200.

Thus, perhaps it would be worthwhile to spend 5.7% more to eliminate the possibility of not having the right gauge of steel? By reviewing the breakdown in design variation, project participants can identify similar strategies for simplifying the production system. Then, with a simpler production system, project participants may be able to improve their ability to execute work reliably.

## 3.8 – Industry Standards and Work Structuring

The Federal Bureau of Prisons (FBOP) developed design guidelines for prison construction in the United States. Since these guidelines can reveal building weaknesses, they are considered proprietary information and can only be accessed by designers and contractors who have been awarded government contracts. The FBOP is the only government entity that has such detailed design requirements, and designers working on federal projects are expected to abide by these guidelines. In contrast, other government agencies might rely more on their architects to determine the design direction.

In 1989, the American Society for Testing and Materials (ASTM) formed Committee F33 on Detention and Correctional Facilities. Committee F33 consists of volunteer representatives from the FBOP, architects, contractors, and detention suppliers. It attempts to develop national standards for prison design criteria and has jurisdiction over standards on detention and correctional facilities that are printed within the Annual Book of ASTM Standards (ASTM 2000). These national standards include design and testing guidelines, but they are not binding – it is up to individual owners to make the standards binding on their projects.

Initially, Committee F33 established standards for doors, hinges, and locks. Then, they developed standards for glazing and door frames. Typically, these standards dictated how long (e.g., 10, 20, 40, 60, or 90 minutes) the components need to resist repeated blows by a 90.7 kg (200-lb) weight before failure. Accordingly, longer duration standards correspond to areas that require higher levels of security. Now, Committee F33 is working on standards for the entire cell envelope including walls, floors, and ceilings.

Innovation in prison design follows an iterative loop between the FBOP's design guidelines, an architect's project-specific design, and Committee F33's testing standards (Figure 32). On federal projects, Committee F33 acts as the regulatory body, FBOP is the owner, and architects develop project-specific designs.

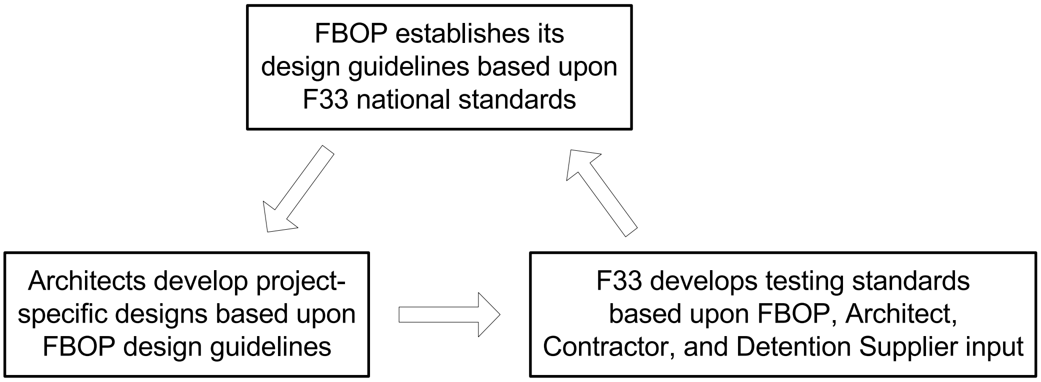

*Figure 32: Process of Prison Design Innovation*

Within Committee F33, Subcommittee F33.02 focuses on walls, ceilings, and hollow metal components. Therefore, if Subcommittee F33.02 outlined performance standards for the interface between frames and walls and recommended strategies for managing this interface, it could promote a more systems-oriented Work Structuring perspective and thus encourage better product-process design integration on future projects.

## 3.9 – Case Study Conclusions

For many capital projects, the creation of open spaces is the primary activity that brings value to the owner. As the primary purpose of a prison is to keep inmates confined, the development of the interface between frames and walls brings considerable value to owners of correctional facilities. When Redgranite's project participants designed, fabricated, and installed hollow metal door frames and precast concrete walls, they treated them as "uncoordinated suboptimized components" (Paulson 1976a). By adopting a systems-oriented Work Structuring perspective, frames and walls can be seen instead as interdependent elements within a cell enclosure system. Then, project participants can identify more global fixes that efficiently develop this comprehensive system.

When problems develop, project participants naturally pursue the simplest solution to avoid disrupting the work of others. This tendency is appropriate if problems are indeed minor, but what if perceived problems are actually indicators of larger Work Structuring problems? Then, as we observed in Case 1, installers apply a local fix to a flawed system, designers remain unaware that their designs contribute to an installation problem, and the same problem reappears in subsequent projects. A cumbersome change order process further discourages project participants from pursuing innovative global fixes.

Case 1 demonstrated how project participants will continue to use an inefficient fix employed on previous projects because it represents a familiar procedure with a predictable outcome – thus, project participants may resist change because they fear losing control of a ‘sure thing.’ Therefore, projects must streamline the change order process and introduce a reward structure for suggesting ideas that improve project development efficiency if they want to foster innovation during construction. Then, by using the 5 WHYs to challenge received traditions in standard practice, projects will have both the incentive and a methodology to think and innovate at a more global level.

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*Table 12: Case 1 Acknowledgments*

| | |
|---|---|
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| **Hensel Phelps Construction** | Jason Burke |
| **Kenrich Products, Inc.** | Rick Rountree |
| **LaForce, Inc.** | Chad Mehlberg |
| **Oldcastle Precast** | Harold Messenger |
| **Rotondo Weirich Enterprises, Inc.** | Connie Mahon |
| **Spancrete Industries Inc.** | John Schnell, Doug Oswald, and Joe White |
| **Tindall Corporation** | Chris Grogan and Frank Grubbs |
| **Truss-Bilt** | Kevin Miller |

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# CHAPTER 4 – STEEL INDIRECT LIGHT FIXTURES

## 4.1 – Case Study Objectives

### 4.1.1 – Understand Current Work Structuring Practice

Work Structuring negotiates the interdependency between (1) establishment of work chunks (i.e., determining *what* must be done to generate value for different project participants), (2) work chunk execution planning (i.e., selecting suitable resources to establish *how* the work chunks will be completed), (3) work chunk sequencing and sizing (i.e., identifying work flows that establish *when* work chunks should be executed and the appropriate rate of production), and (4) determining which production units would be best suited to execute the work chunks (i.e., deciding *who* should execute the work chunks). Case 2, the Steel Indirect Light Fixtures case study, illustrates how a fabricator used new product development and supply chain management to restructure the relationship between these factors to generate an alternative Work Structuring approach for lighting system delivery. In particular, Case 2 describes how an alternative Work Structure using the fabricator's fixtures generates value for different project participants (including electrical contractors, general contractors, and owners).

### 4.1.2 – Develop Methodology for Work Structuring Practice

The selection of project participants (“who”) and products that will be installed on a project (“what”) are major elements of Work Structuring. Case 2 illustrates how these two factors are interdependent with process design development (“how” and “when”) by experimenting with techniques for mapping supply chains, analyzing product and process design integration, mapping Work Structures, conducting a Work Structuring analysis, and expanding the theoretical framework for Work Structuring.

We first develop a supply chain map that illustrates contractual relationships, site access, flows of information, and flows of goods. Next, we consider how the fabricator’s products’ features facilitated product and process design integration. Then, we map a Work Structure involving the fabricator’s products to illustrate the shift in project delivery roles. Subsequently, we examine how the fabricator’s product features illustrate various Work Structuring principles and techniques. Finally, we identify insight from Case 2 into new or modified Work Structuring techniques to expand the Work Structuring framework.

## 4.2 – Lighting Industry Background

### 4.2.1 – Introduction

Two common means of illuminating office space are direct and indirect lighting. Direct parabolic lighting (Figure 33) is often installed into a suspended ceiling grid and shines light directly down into the room. Indirect lighting (Figure 34) is suspended from the ceiling and shines light up against the ceiling and walls so that reflected light illuminates the office space.

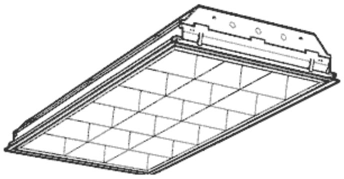


*Figure 33: Direct Parabolic Light Fixture (Williams 2001)*

*Figure 34: Indirect Light Fixture (Linear Lighting 2001)*

Hedge et al. (1995) showed that workers rated indirect lighting more favorably on many subjective lighting impression scales. Approximately two-thirds of the surveyed workers preferred working under indirect light. In particular, indirect light results in less glare on computer screens so workers have fewer problems with eyes getting tired or focusing. Nevertheless, parabolic lighting was the norm until the advent of desktop computers 15-20 years ago helped indirect lighting gain popularity. Subsequently, demand for indirect lighting has increased because computers, and thus glare problems, became ubiquitous.

### 4.2.2 – Supply Chain Map

In the United States, multiple parties make up the lighting supply chain because designers specify a variety of fixture types to manage the different illumination requirements within a project. Figure 35 represents the major players in the lighting supply chain, their contractual relationships, site access during construction and after turnover, communication beyond contractual relationships, and flows of goods (Tsao and Tommelein 2001).

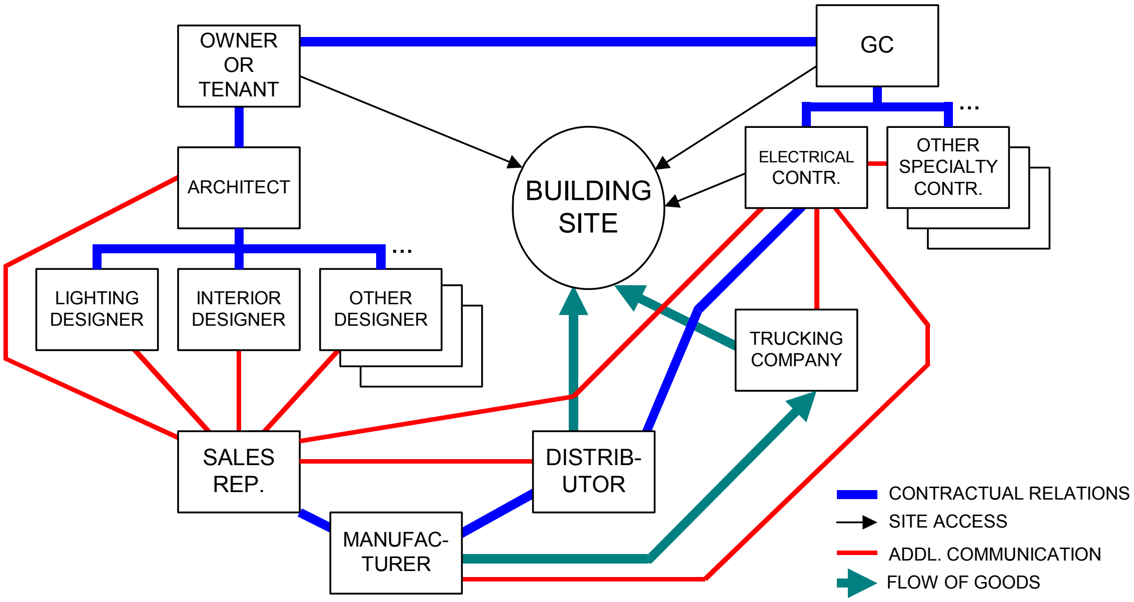


*Figure 35: Lighting Supply Chain (Tsao and Tommelein 2001)*

## 4.2.3 – Contractual Relationships

Typically, an architect's responsibilities include the task of developing lighting plans and specifications. The owner will provide design criteria based on its own needs or that of future end users. The architect may contract with lighting designers and interior designers to assist with different aspects of the lighting design. The architect can also informally solicit lighting design assistance from lighting distributors and fabricator sales representatives (Elder 2000). Lighting distributors typically act as the primary sales representatives for a number of fabricators.

Contractually, the general contractor is responsible for light fixture procurement and installation. The general contractor will then subcontract with an electrical contractor who procures and installs the fixtures in accordance with the final lighting design.

### 4.2.4 – Work Structuring Insight from Contractual Relationships

A combination of factors can generate conflicting priorities among project participants, which in turn contributes to a lighting design that does not meet the needs of the owner. For example: (1) designers might prefer using unique fixtures to demonstrate their skill in achieving a certain aesthetic, (2) installers might prefer fixtures they have bought and installed on previous projects because they expect it would increase their probability of receiving and installing fixtures as planned, (3) greater fixture variety can require additional procedures and skill sets for managing installation, and (4) the local supply chain may have limitations in supply, so the owner compromises aesthetic values in lighting design for a more favorable customer lead time.

Owners need to make their lighting priorities explicit to provide guidance to lighting design development. Do they care if the fixtures on their projects are similar or even identical to the fixtures found on other projects? Are they interested in a consistent or in a variable lighting design from one work space to the next? What level of fixture profile variety do they prefer? If a shorter schedule is a priority, are they willing to use standardized products? These issues should be addressed early in design development.

In the rush to begin design, project participants may risk developing only one lighting design because they expect the end product will match the owner's expectations. Instead, it could be worthwhile for project participants to devote a specific period of time at the onset of design to sort out conflicting customer and stakeholder values. Alternatively, project participants could spend time to consider various options before proceeding with detailed design to support the Level of Influence concept discussed in Chapter 1 in which commitments made during the early phases of a project have "orders of magnitude greater influence on what later expenditures will actually be" (Paulson 1976).

For example, designers might develop 2 to 3 basic lighting designs at the start of design development. These rough designs should represent a range of fixture types and levels of customization to help owners get a sense of fixture variety impact on project quality, schedule, safety, and budget. As a result, designers help owners resolve conflicting values before deciding on a particular level of fixture variety and uniqueness. Otherwise, lighting designers might risk beginning design development at a point where the owner does not want to be in terms of project quality, schedule, safety, and budget.

### 4.2.5 – Flows of Information

Figure 36 illustrates the flows of information during lighting design development. First, the architect develops the basic lighting scheme by deciding which fixtures to use and where they should be located to match the building aesthetic. Lighting designers then calculate the illumination levels by doing point-by-point calculations based upon photometric data provided by fabricators and using architectural backgrounds (Malmgreen 2000). Lighting distributors will often assist with this step, and possibly even perform it at no cost to the designer. If areas are too bright or dark, the lighting designer must adjust the fixtures and their locations to satisfy the customer's lighting requirements. Once the design is set, it is passed back to the architect. The architect then incorporates the lighting design into the project's electrical design.

In a review of specifications across various projects, McKenzie (2001, p. 15) found the following breakdown of light fixture specification:

*Table 13: Light Fixture Specification (McKenzie 2001)*

| **Single Brand** | **Multiple Brand** | **"Of Equal" to Named Brand** | **Performance Spec. (no brand named)** | **Total NOT Single Brand** |
|---|---|---|---|---|
| 10% | 38% | 49% | 3% | 90% |

However, since it is difficult for electrical contractors to make satisfactory substitutions, the contract for supplying the "'Of Equal' to Named Brand" option will often go to the named fabricator. Consequently, lighting distributors stay in constant communication with designers to persuade them to specify the fabricators they represent (Elder 2000). In general, distributor tasks include: (1) assisting designers with point-by-point illumination calculations, (2) keeping tabs on the fabricators' current volumes to ensure that the fabricators they promote to lighting designers are capable of handling new orders, (3) keeping abreast of any new products being planned by the fabricators, which can be marketed to designers, and (4) staying in touch with electrical contractors because they are usually responsible for soliciting bids and purchasing fixtures from suppliers.

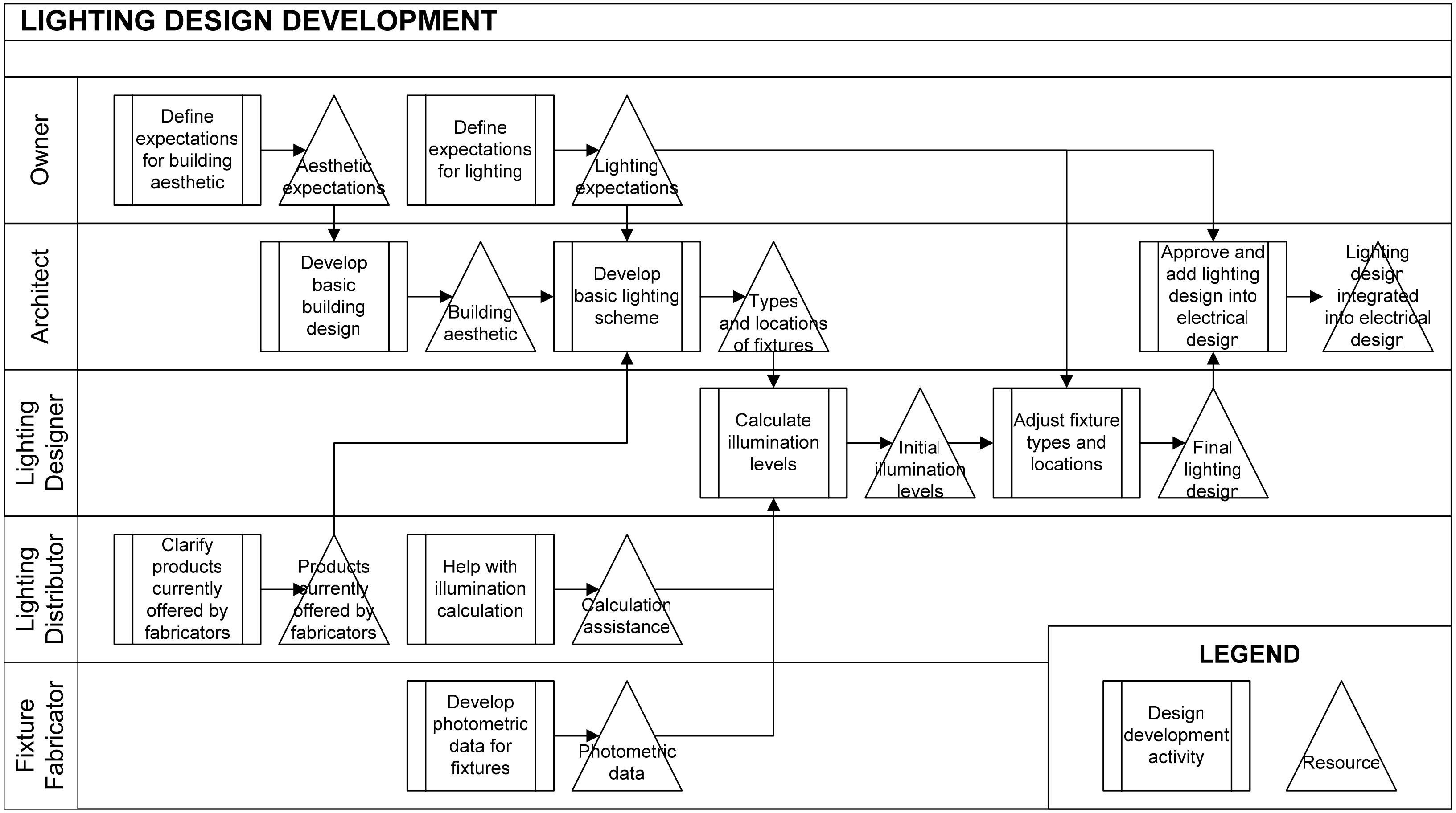


*Figure 36: Lighting Design Development*

Electrical contractors often get distributors to supply all products that cover the entire lighting package because distributors generally have a stronger financial credit line and more clout with fabricators than do contractors (Elder 2000). Once the electrical contractor picks a distributor to supply the lighting products, the contractor will issue purchase orders to the distributor. As a result, fabricator sales representatives need to go through the distributor to learn about the status of purchase orders. Once a purchase order is issued, the fabricator works with the contractor to review the architect's lighting design and obtain shop drawing approval. Upon approval, the fabricator will pull fixtures from stock or make or assemble them to order and then arrange for delivery to the electrical contractor, usually by shipping directly to the site. Because of product variety, customization requirements, and cost, distributors seldom keep fixtures in inventory, so they hold contracts with fabricators to supply fixtures on an "as-needed" basis. Should the electrical contractor have any difficulty with the fixtures, they can contact the lighting distributor or the fabricator, depending on the agreement.

### 4.2.6 – Work Structuring Insight from Flows of Information

Due to their familiarity with fabricator products, lighting distributors are well-positioned to bring Work Structuring advantages to the attention of owners and architects. Distributors can promote fabricators whose products can be mass customized to meet the changing needs of customers. Distributors can also track the reliability of their fabricators in meeting procurement deadlines and provide this data to owners and architects if it sheds a favorable light on their fabricators. If distributors find some fabricators consistently miss performance commitments (e.g., performance in terms of cost, schedule, or quality), they need to challenge these fabricators to improve their reliability in meeting commitments or risk being excluded on future projects. Thus, by promoting more flexible and reliable fabricators, distributors can encourage owners and architects to appreciate and account for the impact of their product design choices on process design.

### 4.2.7 – Flows of Goods

After finishing an order, the fabricator will hire a trucking company to deliver the fixtures either in staged deliveries or a single delivery to the electrical contractor at the building site. If the electrical contractor has access to the location(s) where fixtures will be installed, fixtures may be staged there upon delivery to avoid future re-handling.

### 4.2.8 – Customer Requirements

The primary customers of light fixture fabricators include owners, designers, and electrical contractors.

Owners establish the requirements that guide fixture selection by designers (including architects and lighting specialists). For example, owners may want fixtures that:

- are inexpensive (or perhaps expensive ones to show prestige)
- blend into the interior design (or perhaps stand out as a highlight)
- are easy to maintain
- can be procured without delaying the project.

Owners may also authorize changes if they feel design adjustments are worthwhile.

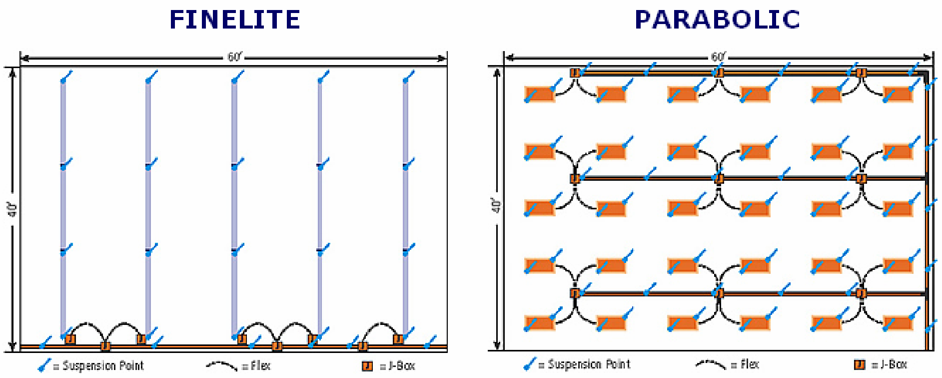
Designers may select fixtures based on architectural qualities, performance (e.g., the quality of the light vs. energy consumption), life-cycle issues (e.g., maintenance needs and durability), and cost (Malmgreen 2000). Designers can be the most important factor behind fixture selection since they decide on the fixture types when developing the basic lighting scheme.

Electrical contactors procure fixtures based on design specifications. If specifications allow some procurement flexibility, electrical contractors might have the option to select fixtures they have installed on previous projects. Electrical contractors may prefer fixtures that are easy, quick, and safe to install. In addition, they value timely and reliable delivery and prefer packaging that prevents all breakage. However, as mentioned earlier, electrical contractors may have no procurement flexibility if the designers select products of a specific fixture fabricator for the lighting design.

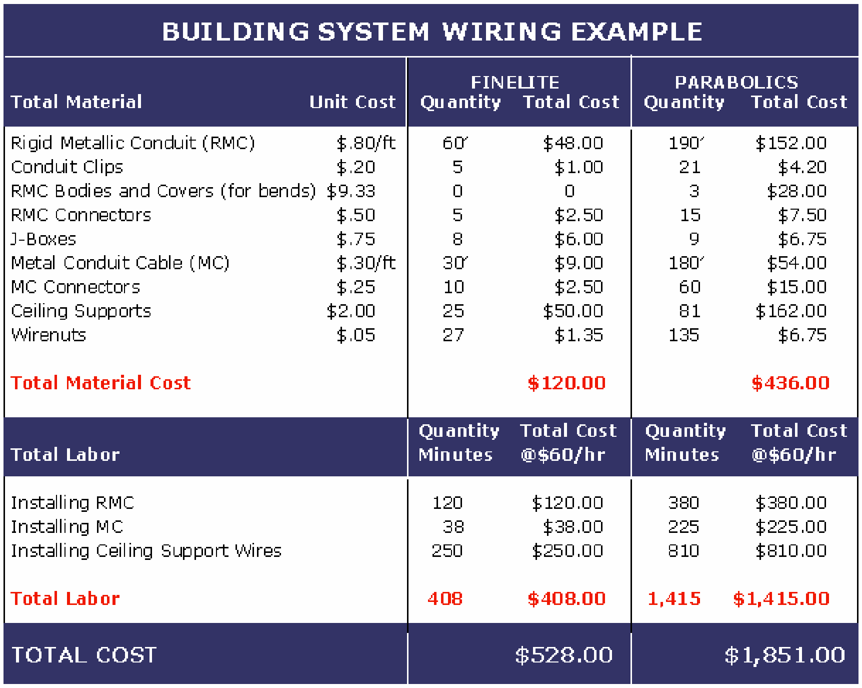
## 4.3 – Company Background

The focus of Case 2 is Finelite, an indirect light fixture fabricator based in Union City, CA. Founded in 1991, Finelite developed an alternative indirect lighting system to compete with direct parabolic lighting. Before Finelite entered the lighting industry, indirect fixture fabricators offered numerous design options in the form of fixture profiles and colors to attract business from high-end owners and architects. In doing so, these fabricators had 4- to 6-week lead times if not longer in fulfilling customer orders due to the custom nature of every order. Consequently, indirect light fixtures had difficulty competing with direct parabolic light fixtures whenever owners prioritized schedule performance. However, as mentioned earlier, an indirect lighting system provided better quality lighting in comparison to direct parabolic light fixtures, especially for the Dot-com projects of the late 1990s, because they created less glare on computer screens.

In response, Finelite developed indirect light fixtures that could compete against direct parabolic fixtures in terms of quality and other indirect light fixtures in terms of schedule and cost. After investing in new product development, Finelite began shipping indirect fixtures with standardized profiles that (1) could ship in 10 working days following order receipt and (2) were easier to lay out and install (Finelite 2000). Subsequently, Finelite promoted how its steel fixtures had lower total installation cost and shorter installation duration compared to direct parabolic fixtures (Figure 37).



This example illustrates the difference between a site wired for Finelite compared to one wired for parabolic fixtures. The total installation cost for Finelite is one-third the cost of installing parabolics.



**BUILDING SYSTEM WIRING EXAMPLE**

| Total Material | Unit Cost | FINELITE Quantity | FINELITE Total Cost | PARABOLICS Quantity | PARABOLICS Total Cost |
|---|---|---|---|---|---|
| Rigid Metallic Conduit (RMC) | $.80/ft | 60' | $48.00 | 190' | $152.00 |
| Conduit Clips | $.20 | 5 | $1.00 | 21 | $4.20 |
| RMC Bodies and Covers (for bends) | $9.33 | 0 | 0 | 3 | $28.00 |
| RMC Connectors | $.50 | 5 | $2.50 | 15 | $7.50 |
| J-Boxes | $.75 | 8 | $6.00 | 9 | $6.75 |
| Metal Conduit Cable (MC) | $.30/ft | 30' | $9.00 | 180' | $54.00 |
| MC Connectors | $.25 | 10 | $2.50 | 60 | $15.00 |
| Ceiling Supports | $2.00 | 25 | $50.00 | 81 | $162.00 |
| Wirenuts | $.05 | 27 | $1.35 | 135 | $6.75 |
| **Total Material Cost** | | | **$120.00** | | **$436.00** |
| **Total Labor** | | **Quantity Minutes** | **Total Cost @$60/hr** | **Quantity Minutes** | **Total Cost @$60/hr** |
| Installing RMC | | 120 | $120.00 | 380 | $380.00 |
| Installing MC | | 38 | $38.00 | 225 | $225.00 |
| Installing Ceiling Support Wires | | 250 | $250.00 | 810 | $810.00 |
| **Total Labor** | | **408** | **$408.00** | **1,415** | **$1,415.00** |
| TOTAL COST | | | $528.00 | | $1,851.00 |

*Figure 37: Building System Wiring Example (Finelite 2002)*

Thus, with its achievements in delivery, installation, and lighting quality, Finelite reshaped lighting system delivery by generating greater value for its customers: electrical contractors, designers, owners, and future building occupants.

## 4.4 – Analysis of Product-Process Design Integration

With its efforts in new product development, Finelite carefully balanced product design and process design for lighting system delivery. In particular, it developed innovative changes in product design of indirect fixtures to improve off-site assembly and job-site installation. Then, by outsourcing various production steps to its suppliers, Finelite increased its production agility to promptly handle orders for different product families. We next illustrate Finelite's management of product and process design integration by describing and analyzing specific features of its indirect lighting system.

### 4.4.1 – Steel Fixtures instead of Aluminum

When the indirect lighting market emerged, most fabricators made fixtures from extruded aluminum because designs often called for unique, lightweight profiles. However, extruded aluminum is an expensive material, so indirect aluminum fixtures developed a reputation for being a luxury item. As a consequence, designers reserved them for lighting important spaces such as conference rooms. As the indirect lighting market matured, fabricators began introducing fixtures made of rolled steel which were significantly less expensive material-wise (aluminum costs about three times as much as steel). In addition, since steel is stronger, less material is required to provide the same amount of structural support. However, many architects considered steel fixtures to be inferior in quality, so they continued to specify only aluminum fixtures.

Not many aluminum extruders exist since extruding equipment requires considerable investment to setup and maintain. As a result, only a few aluminum extruders service many industries, so extrusions are expensive and typically take 4 to 6 weeks to procure. Thus, steel might provide a favorable alternative since it is more readily available and multiple suppliers can roll, bend, punch, and paint it. Having many raw materials suppliers and steel fabricators helps reduce uncertainties in fixture production while increasing the likelihood of competitive pricing. Furthermore, the process of shaping sheet steel into a finished fixture body can be faster and more flexible than the extrusion process resulting in shorter lead times for fixture procurement. However, compared to aluminum, steel is harder to shape within the tolerances needed for fixture alignment and prevention of light leakage at joints.

Finelite accepted this challenge and spent 3 years on product development before releasing its first fixture family. In that period, it worked out a process for preparing and painting cold-formed steel with the help of local steel fabricators. This effort yielded rolled steel fixtures that resembled extruded aluminum fixtures and achieved the high tolerances required for installation and operation. Then, Finelite worked on convincing owners and architects that its steel fixtures were capable of replacing aluminum fixtures without any detriment to lighting system quality.

### 4.4.2 – One Shade of White

Fabricators typically use powder coating systems to electrostatically apply finishes to light fixtures. Whenever an order requires a different shade or color, a technician needs to vacuum the powder coating equipment to prevent specks of the previous color from showing up on the next order. As a result, offering different fixture shades or colors increases the likelihood of required setups for switching colors, and each setup contributes to longer manufacturing lead times.

Since Finelite wanted to achieve shorter lead times for its fixtures, it decided to offer only one shade of white to simplify its production process. This also enabled it to have its suppliers take care of painting the steel profiles. In contrast, other fixture fabricators may offer 5 to 6 shades of white and take care of painting themselves. Finelite also offered the option of picking from a standard set of colors to its customers. However, doing so adds considerable cost to the fixture order in terms of time and money, so most orders call for Finelite’s standard shade of white.

Instead of limiting customers to one shade of white, a fixture fabricator may work on reducing setup times for switching paint colors as an alternative strategy for reducing manufacturing lead times.

### 4.4.3 – Limited Product Families

Light fixtures can have long lead times in part because they require (1) custom production dies for forming raw materials into fixture profiles or (2) custom colors for the fixtures’ finishes. Starting in 1994, Finelite introduced a new product family approximately every 8 months. Each product family conformed to a specific fixture profile, and Finelite did not accept orders for custom profiles. This decision required investing more resources upfront to develop standardized fixtures, but it allowed Finelite to gain economies of scale from reusing the same production dies to form different orders using the same fixture profile for a specific product family. Combining this with an encouragement to accept its only shade of white, Finelite managed to convince many owners and architects to allow for standardized fixtures on their projects in exchange for the benefits of shorter manufacturing lead times and ease of on-site installation. In addition, Finelite's decision to use limited product families allowed it to maintain approximately 2 weeks worth of inventory at its own facilities.

### 4.4.4 – 10-Day Lead Time

Finelite identified cutting, rolling, punching, and painting of fixtures as production steps that could be outsourced to upstream suppliers (Venkatesan 1992). Then, by combining this outsourcing strategy with its decision to offer only standardized fixtures, Finelite was able to manage its raw materials inventory in "vanilla box" configurations to postpone customization of its fixtures (Feitzinger and Lee 1997, Signorelli and Heskett 1984). At its own facilities, Finelite took care of final assembly and wiring of fixtures which must be done to order since wiring is a function of the number and location of switches within a room. Since these steps do not take very long, Finelite was able to move the Customer Order Decoupling Point (CODP) much further downstream.

As a result, Finelite could commit to delivering products to site with a 10-day lead time from receipt of the contractor's release order, following the approval of shop drawings. Shorter fixture lead times are especially useful for quick projects, where competing fabricator's lead times may even exceed the project duration. In addition, a reliable fixture lead time of 10 days helps electrical contractors 'pull' fixtures from the fabricator in a time frame that falls within their 4-to-6-week lookahead planning window to synchronize deliveries with installation tasks. Furthermore, shorter fixture lead times help electrical contractors reduce laydown space and double handling because they can plan to store the fixtures on the building site for shorter amounts of time.

### 4.4.5 – Integer Fixture Lengths

When Finelite entered the indirect lighting market, competitors provided light fixtures that were not exact integers in length. This happened because the lamps used in light fixtures at that time were 4’ (1.2 m) long, so most fixtures were slightly larger[1]. This made it difficult to install fixtures on 2-foot and 4-foot ceiling grid T-bars. Then, electrical contractors had to drill holes through ceiling tiles to install the fixtures. To improve the installation process for electrical contractors, Finelite developed fixtures that were exactly 4’-0” or multiples in length, made within a tolerance of 0.005” (0.1 mm), to match the ceiling grid (Figure 38).

*Figure 38: Integer Fixture Lengths Matching Ceiling Grid (Finelite 2001)*

With integer fixture lengths, contractors did not need to measure and mark installation locations. Rather, they could count ceiling grid T-bars to determine fixture locations. Thus, since electrical contractors did not need to spend labor or equipment on measuring, installation could proceed quickly. Integer fixture lengths also provided an aesthetic advantage in terms of alignment over fixtures that did not match ceiling grids.

## 4.4.6 – Pre-Wiring

Wiring fixtures at the job-site is a lengthy task because it requires electrical contractors to refer to a wiring diagram that accounts for the number and location of switches within each room. Finelite believed its shop workers would be more efficient at wiring fixtures because the controlled off-site environment eliminated interruption by other job-site trades. Consequently, it developed a channel that facilitated pre-wiring by securing wires inside fixtures (Figure 39). Pre-wiring simplified job-site installation since electricians no longer needed to manage wiring customization.

*Figure 39: Wire Management Channel (Finelite 2002)*

The shift of work from job-site electricians to off-site shop workers reduced overall total-installed-cost (Figure 37) and increased wiring quality for fixtures. In addition, since their job-site wiring duties were reduced to wiring power feed locations, electricians could increase their reliability in executing planned work.

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[1] The newer, high-efficiency T5 lamps are shorter in length. When T5 lamps were finally introduced to the North American market in 1996 (DiLouie 2005), competing fabricators could easily develop fixtures that matched the ceiling grid.

However, the benefit of pre-wired fixtures introduced a new challenge in materials management – electricians had to match each fixture to its pre-determined location. If fixtures were pre-wired incorrectly, electricians could not make substitutions easily – instead, they may need to re-order faulty fixtures. Consequently, Finelite had to maintain high levels of quality if it wanted electrical contractors to switch to pre-wired fixtures.

## 4.4.7 – Mated Plugs and Joining

Sometimes electrical contractors are responsible for stripping wires and connecting them between fixtures. Finelite developed mated plugs and die-formed interlocking parts so that the electrical contractor can quickly connect light fixtures to each other (Figure 40).

*Figure 40: Mated Plugs and Interlocking Fixture Ends (Finelite 2002)*

The interlocking parts have 0.005” (0.1 mm) tolerances that prevent light from leaking through and thus make the seams almost invisible. Thus, mated plugs and interlocking fixture ends introduced poka-yoke (i.e., a built-in mechanism that prevents mistakes) devices to help reduce variability in installation conditions (dos Santos and Powell 1999).

Through pre-wiring, Finelite established each fixture as a ‘starter’, ‘joiner’, ‘ender’, or ‘independent’ fixture. Starters are fixtures that connect directly to the electrical source.

Enders are fixtures that conclude a run of fixtures. Joiners are fixtures that fit in between starters and enders. Independents are fixtures that are not connected to any other fixtures. Thus, since a run of fixtures containing a starter, joiners, and an ender uses a single power feed, Finelite can manage long runs (in 4-foot increments) of indirect light fixtures to uniformly illuminate practically any length of indoor space.

## 4.4.8 – Mounting System

To further take advantage of modular lengths, Finelite developed a mounting system that attached directly to the ceiling grid T-bars (Figure 41). As a result, electrical contractors could install fixtures before the ceiling tiles were brought in, which improves installation flexibility. In addition, the ability to mount the clips at any location on a T-bar gave contractors more leeway to properly align the fixtures during installation (Figure 42).

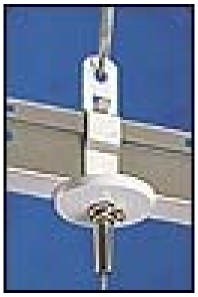

*Figure 41: Mounting System Attached to T-bar (Finelite 2002)*

*Figure 42: Flexibility of Mounting System (Finelite 2002)*

Use of the clips in effect de-coupled the electrical contractors' work from ceiling tile installation. Thus, contractors no longer had to wait for the ceiling tiles to be installed and they no longer had to drill any holes in ceiling tiles. In addition, it took only a few minutes to install each mounting clip.

The mounting system was designed so that ceiling tiles lay flat when placed over the mounting clips, whereas some other fabricator’s clips resulted in tilted tiles. The mounting system also allowed the ceiling tiles to remain removable for maintenance or replacement efforts in the future.

## 4.4.9 – Hanging Support Package

Finelite developed a hanging support package for fixtures that need to be installed in open ceilings (Figure 43). An open ceiling is considered to be an ‘unknown site condition’ because there is no ceiling grid that could be used as a reference point for hanging fixtures.

*Figure 43: Fixture Installed in an Open Ceiling*

The hanging support package for open ceilings contains cables and accompanying parts. Cables come in 8 standard lengths from 6” up to 150” (15 – 380 cm) and they are delivered in bags of 100 for faster count verification. The cables are produced in batches and cut into standard lengths because a high-tonnage press needs to attach a safety crimp on one end of each cable. Electrical contractors might order one of the standard lengths for a project and then, if necessary, cut the cables to the final length on site. In addition, electricians may require additional cable length to maneuver around a fire sprinkler in the way of installation or account for varying ceiling height within a section of the building.

### 4.4.10 – Leveling

Leveling a series of connected fixtures is not an easy task. Since unleveled fixtures can be detected by the naked eye, leveling is also an important aesthetic task, especially in the case of long runs of fixtures. Finelite developed a leveling process that allowed electrical contractors to quickly adjust the suspension heights of fixtures should last-minute design changes or other causes make it necessary. For the leveling process, the electrician:

1. Lifts the first fixture into place and levels both ends.
2. Screws in a top lock nut at the beginning of the run to hold the cable in tightly.
3. Attaches the second fixture, levels the free end, and then levels the connected end.
4. Screws in a top lock nut at the connected end to hold the cable in tightly.
5. Repeats Steps 3 and 4 until finishing the run of fixtures.
6. Screws in a top lock nut at the end of the run to hold the cable in tightly.

Thus, this adaptable process allowed electricians to easily level a run of fixtures.

### 4.4.11 – Pre-lamping

Many parabolic fixtures and competing indirect light fixtures required the installation of lamps on the job-site. Finelite developed fixture body and packaging designs that allowed fixtures to ship pre-lamped from the manufacturing shop. Pre-lamping is optional and costs extra, but many electrical contractors prefer it because it speeds up installation. Pre-lamping eliminated the need to store and handle lamps on site. It transferred the task of lamp installation from electricians to shop workers who work more efficiently at table height, in a safer environment, and at a lower pay scale. Pre-lamping also freed up site space and time for electricians. To allow use of fixtures during construction, Finelite wrapped plastic around the pre-lamped fixtures to help keep them clean (Figure 44).

*Figure 44: Pre-Lamped Fixtures Wrapped in Plastic*

This assumes that owners will not object to lights being used prior to building occupancy – there is an anecdote of an owner demanding that 'used' lights be replaced at turnover.

### 4.4.12 – Packaging and Palletizing

Finelite developed new packaging using cardboard or Styrofoam boxes to minimize breakage and allow for stacking and palletizing of its fixtures. As a result, companies could transport fixtures with a very low rate of fixture breakage (Figure 45). Palletizing also removed the need to manually re-handle individual fixtures as is the case with some competitor products.

*Figure 45: Lifting Palletized Fixtures onto an Upper Floor*

There is no cost difference between cardboard and Styrofoam packaging. If electrical contractors plan to install fixtures in 4 to 6 months, they might order cardboard packaging because it protects fixtures better from construction debris and minor collisions.

Boxes could be reused once fixtures have been installed. Electrical contractors could return boxes by stacking them on pallets and then moving pallets to a loading area for Finelite to pick up. Most electrical contractors do not ask to be reimbursed for the time it takes to collect and prepare the used packaging because the effort required is minimal and the recycling also helps dispose of waste. This system worked well for repeated deliveries (i.e., delivery trucks returned with empty packaging) and in areas where Finelite had several projects going on at the same time (e.g., the San Francisco Bay Area).

### 4.4.13 – Sequencing

For electrical contractors who plan with greater reliability, Finelite could package light fixtures onto pallets to match specific installation sequences. This packaging benefit required electrical contractors to plan in more detail and longer in advance than usual. It also assumed that a given sequence will not be impeded by trade interference or other project uncertainties. Similarly, Bernold and Salim (1993) showed that rebar can be micro-bundled ahead of time by the steel supplier to match site use plans, and Ballard et al. (2002) described how precast concrete fabrication can be restructured to better support installation on construction projects.

In addition, Styrofoam packaging allowed electrical contractors to easily remove individual fixtures from the middle or bottom of a stack (Figure 46). This provided electricians more flexibility when they installed light fixtures, should advance sequencing not be feasible.

*Figure 46: Fixtures in Styrofoam Packaging*

### 4.4.14 – Impact of Product-Process Design Integration

Table 14 illustrates Finelite's management of product and process design integration from a Work Structuring perspective. From Table 14, we can see how Finelite's changes in both supply chain design and product design generated improvements in both process design and operations design. These efforts then facilitated improved performance in lighting system delivery, especially in terms of schedule and budget. Thus, owners who are willing to use standardized indirect light fixtures on their projects can potentially benefit from improvements in schedule and budget performance.

*Table 14: Product-Process Design Integration by Finelite (“Δ” = Changes, “+” = Positive Impact, “–” = Negative Impact)*

| FEATURE | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| Steel fixtures | Δ | Δ | + | | | | + | + |
| One shade of white | Δ | Δ | + | | | – | + | + |
| Limited product families | | Δ | + | + | | – | + | + |
| 10-day lead time | Δ | Δ | + | | | | + | + |
| Integer lengths | | Δ | | + | | + | + | + |
| Pre-wiring | Δ | Δ | + | + | + | + | + | + |
| Mated plugs and joining | Δ | Δ | + | + | + | + | + | + |
| Mounting system | | Δ | | + | + | + | + | + |
| Hanging support | | Δ | | + | | + | | |
| Leveling | | Δ | | + | | + | + | + |
| Pre-lamping | Δ | Δ | + | + | + | + | + | + |
| Packaging and palletizing | | Δ | + | + | | | + | + |
| Sequencing | | Δ | | + | | | + | + |

## 4.5 – Work Structure Mapping

Finelite's efforts in new product development shifted work among project participants in lighting system delivery. Specifically:

- Work (i.e., installation of wiring, plugs, and lamps into fixtures at the job-site) normally performed by the electrical contractor shifted to the fixture fabricator, thus moving on-site work into shop conditions (Ballard and Howell 1998).
- Work (i.e., cutting fixture lengths, punching holes, and painting) normally performed by the fixture fabricator shifted to a roll forming supplier.

These supply chain changes, combined with adjustments in product, process, and operations designs, allowed Finelite to generate an alternative Work Structure that could challenge other lighting systems (i.e., those using parabolic direct light fixtures or aluminum indirect light fixtures).

Figure 47 represents Finelite's delivery process in the form of a Work Structure map. Each row represents work performed by one production unit – in this case, the roll forming fabricator, fixture fabricator, and electrical contractor. The arrangement of work chunks illustrates sequencing and work flow, bold boxes indicate shifts in responsibility for work chunk execution, and bold text indicates work affected by Finelite's new product development efforts. We also note when work chunks help customize fixture features within the production system.

## 4.6 – Work Structuring Analysis

Ballard et al. (2001) outlined ends-means hierarchies to guide efforts in Work Structuring. Focusing on maximizing value and minimizing waste, these hierarchies "progressively answer the question 'What should we do to achieve a goal?', moving from desired ends to actionable means" (Ballard et al. 2001). We use these ends-means hierarchies as a starting point for identifying and developing effective Work Structuring principles and techniques.

The following sections analyze how Finelite's products' features illustrate lower-level Work Structuring principles and techniques as identified by the hierarchies, and we summarize our findings in Tables 15 and 16. When fixture features uncover ideas for new or modified Work Structuring techniques, we indicate adjustments to Ballard et al.'s ends-means hierarchies with bold text within the tables.

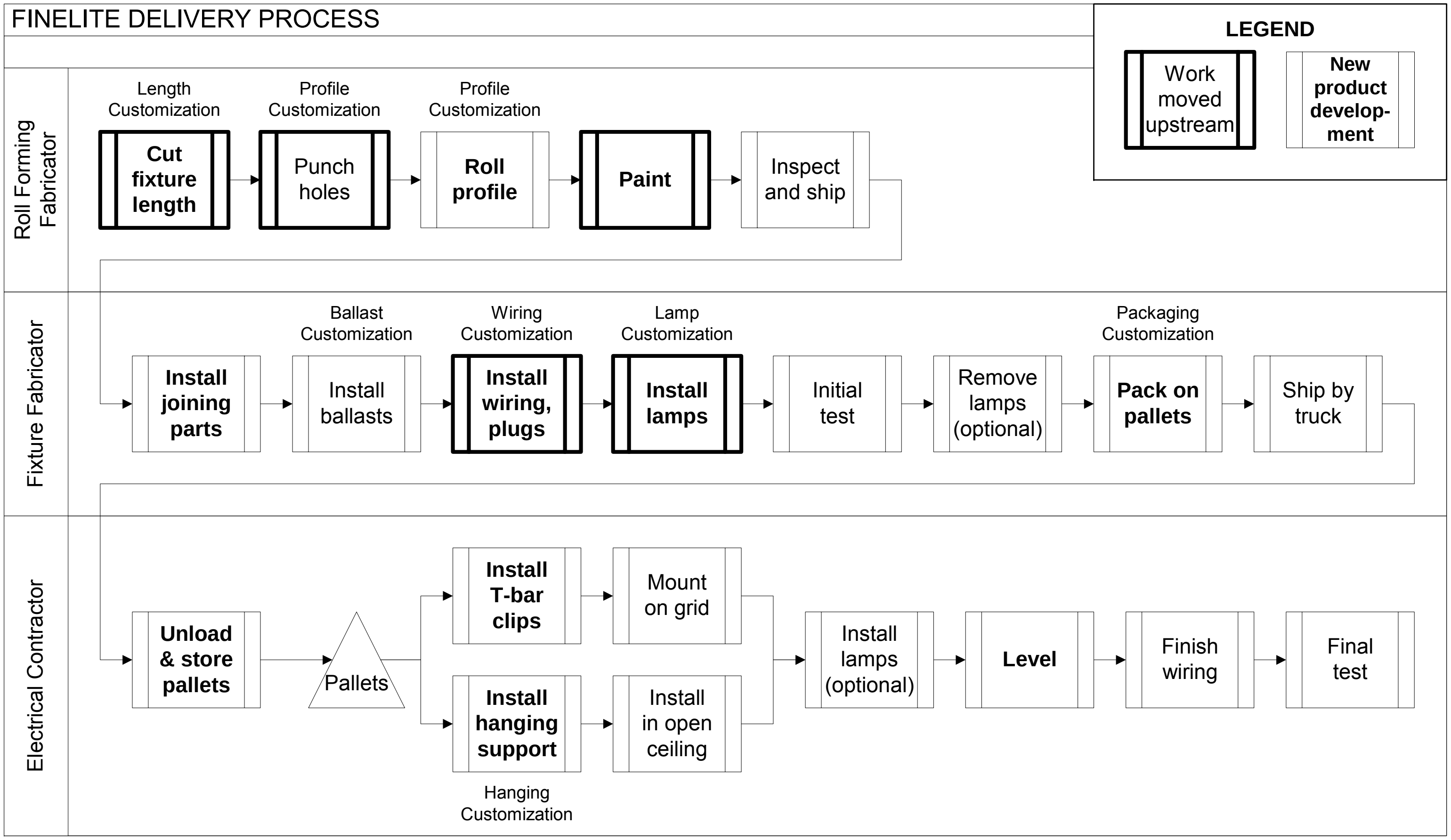

*Figure 47: Work Structure of Finelite Delivery Process*

*Table 15: Case 2 Insight into Work Structuring Principles and Techniques*
*(**bold** = adjustments to Ballard et al. 2001 ends-means hierarchies)*

| *HIGHER-LEVEL WORK STRUCTURING PRINCIPLES* | *LOWER-LEVEL WORK STRUCTURING PRINCIPLES* | *WORK STRUCTURING TECHNIQUES* | *Steel fixtures* | *One shade of white* | *Limited product families* | *10-day lead time* | *Integer lengths* | *Pre-wiring* | *Mated plugs and joining* | *Mounting system* | *Hanging support* | *Leveling* | *Pre-lamping* | *Packaging and palletizing* | *Sequencing* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Make materials and information flow / reduce cycle times | Structure work for flow | Type, size, and locate buffers for variability | X | | X | | | X | | | X | | | | X |
| | | Make production rate = demand rate | | X | X | | | | | | | | | | |
| | | **Structure for flow at supplier's facilities** | X | X | X | | | | | | | | | | |
| | | **Structure for flow between supplier and fabricator** | X | X | X | | X | | | | | | | | |
| | | **Structure for flow at fabricator's facilities** | | | X | | | | | | | | | X | |
| | | **Structure for flow between fabricator and job site** | | | | X | | | | | | | | X | |
| | | **Structure for flow at job site** | | | | X | X | X | X | X | | X | X | | X |
| | | Simplify site work to final assembly | | | | | | X | X | X | | X | X | | |
| | | Minimize negative iteration in design | | X | X | | X | | | | | | | | |
| | | **Reduce bad variability** | | | | | | | | X | X | | | | X |
| | | **Increase product/process safety** | | | | | | X | X | | | | X | | |
| | Reduce inspection times | Make inspection unnecessary/automatic | | | | | X | X | X | | | | X | | |
| | | Incorporate inspection into processing | | | | | | X | X | | | | X | | |
| | Reduce rework time | Perform in-process inspection | | | | | | X | X | | | | X | | |
| | | Act on causes of defective work | | | | | | X | X | | | | X | | |
| | | **Simplify products to limit mistakes** | | X | X | | X | | | | | | | | |
| | Control work for flow | **Increase process transparency** | X | | | | X | | | | | | | X | X |
| | Reduce processing times | Reduce process batches | | | | X | | | | | | | | | |
| | | Apply technology | X | | X | | | X | X | X | | X | | | |
| | | Redesign products less processing | X | | X | | | X | X | X | | X | | | |
| | | **Develop consistent interface conditions** | | | | | X | | X | X | | | | | |
| | Reduce inventories | **Reduce bad variability** | X | X | X | | X | | | | | | | | |
| | | Reduce setup times | X | X | X | | X | | | | | | | | |
| | | Pull materials and information when possible | X | | X | | | | | | | | | | |
| | Reduce resources spent being moved and not processed | Reduce 'distances' | X | | | | | | | | | | | | |
| | | Increase movement speed | | | | | | | | | | | | X | |
| | | Reduce number of moves | | | | | | | | | | | | | X |

*Table 16: Case 2 Insight into Work Structuring Principles and Techniques (**bold** = adjustments to Ballard et al. 2001 ends-means hierarchies)*

| *HIGHER-LEVEL WORK STRUCTURING PRINCIPLES* | *LOWER-LEVEL WORK STRUCTURING PRINCIPLES* | *WORK STRUCTURING TECHNIQUES* | *Steel fixtures* | *One shade of white* | *Limited product families* | *10-day lead time* | *Integer lengths* | *Pre-wiring* | *Mated plugs and joining* | *Mounting system* | *Hanging support* | *Leveling* | *Pre-lamping* | *Packaging and palletizing* | *Sequencing* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reduce defective products | Improve supplier quality and on-time delivery | Reduce suppliers and engage in lean | X | X | X | | | | | | | | | | |
| | | Actively learn with suppliers | X | | X | | | | | | | | | | |
| | | **Standardize orders to suppliers** | | X | X | | | | | | | | | | |
| | | **Set supplier production based on fabrication** | | | | X | | | | | | | | | |
| | Improve quality of intermediate products | Improve design constructability | | | | | X | | | X | X | X | | | |
| | | Use in-process inspection | | | | | | X | | | | | X | | |
| | | **Protect products from breakage** | | | | | | | | | | | | X | |
| Get more from less | Increase resource productivity | Increase resource utilization | | | | | | | | | | | | X | |
| | | Increase resource fruitfulness | | | | | | | | | | | X | | |
| | | Assign tasks where best done | | X | | | | X | X | | | | X | | |
| | Reduce cost of using materials and information | Reduce material scrap | | | | | | X | | | X | | | X | |
| | | Reduce unneeded work space | | | | | | X | | X | | | X | | X |
| | | Reduce 'emissions' | X | | | | | | | | | | | | |
| | Reduce acquiring cost for resources | Reduce transaction costs | | | X | | | | | | | | | | |
| | | Reduce purchase prices | X | X | X | | | | | | | | | | |
| Help customers accomplish purposes | Understand, critique, and expand customer purposes | Design for all life cycle stages | | | | | | | X | | | | X | | |
| | | Inspect against purposes | | | | X | | | | | | | | | |
| | Structure work for value | Align stakeholder interests | X | X | X | X | X | X | X | X | X | X | X | X | X |
| | Increase system control | Focus control on complete system | | | | X | | | | | | | | | |
| | | Simplify the system | | X | X | | X | | | | | | | | |
| | | Increase system transparency | X | | | | | | | | | | | | |
| | | **Increase good variability** | | | X | | X | | | | X | | | | |

### 4.6.1 – Structure Work for Flow

Both aluminum and steel fixtures require die production for forming fixture profiles. However, Finelite's decision to use limited product families streamlined supplier work flow by reusing existing production dies. During final assembly, Finelite maintained buffers of electrical wiring to absorb pre-wiring variability. During installation, Finelite's hanging support system provided buffers to handle varying ceiling heights and Styrofoam packaging helped electricians handle varying installation sequences.

Finelite's push for one shade of white, limited product families, and integer fixture lengths helped minimize negative iteration in design by limiting choices in fixture colors, profile shapes, and lengths.

Ballard et al.'s (2001) techniques of "Use continuous flow processes where possible" and "Layout for flow" could be further clarified as:

- "Structure for flow at the supplier's facilities"
- "Structure for flow at the fabricator's facilities"
- "Structure for flow at the job-site".

Ensuring continuous work flow at the job-site through efforts such as prefabrication can transfer buffers of work-in-progress to the fabricator's facilities. Ensuring continuous work flow at the fabricator's facilities through efforts such as modularization can transfer buffers of work-in-progress to the supplier's facilities. As a result, project participants must coordinate their efforts and balance the production system across the different stages of production to make sure one project participant does not constantly have to bear the burden of carrying considerable work-in-progress.

The decision to use steel facilitated better flow at the fabricator's facilities since steel is easier to procure than aluminum. The push for one shade of white and limited product families also helped facilitate flow by reducing the number and types of setups at the supplier's facilities. Fewer product families helped shop workers at the fabricator's facilities manage familiar final assembly work based on a limited range of fixture profiles. The Styrofoam packaging system also allowed the packaging process to keep up with final assembly. Finally, the 10-day lead time, integer lengths, pre-wiring, plugs and joining, mounting system, leveling, pre-lamping, and sequencing features helped electricians structure for flow at the job-site.

In addition to structure for flow at the supplier, fabricator, and job-site, we can also:

- "Structure for flow between the supplier and fabricator"
- "Structure for flow between the fabricator and job-site".

Finelite's alliances with its suppliers allowed it to maintain approximately 2 weeks worth of inventory. It could pull a steady flow of fixtures from its suppliers because of its use of steel, one shade of white, limited product families, and integer lengths. Then, Finelite's commitment to a 10-day lead time and ability to palletize fixtures helped it provide a steady flow of fixtures to the job-sites of its customers.

Finelite's fixture features of pre-wiring, mated plugs and joining parts, on-grid mounting system, leveling system, and pre-lamping each contributed to making installation quicker and easier. This helped transform site work into final assembly work and testing. However, when fixtures need to be installed into open ceilings, the hanging support system requires additional processing by the electrical contractor before installation.

Reducing “bad variability” helps structure work for flow. “Bad variability” (e.g., “unplanned outages, quality problems, operator variation, and inadequate design”) is “an undesired side effect of a poor operating policy” (Hopp and Spearman 2001, p. 288). “While (bad) variability may be unavoidable, it is not something we would deliberately introduce into the system.”

Finelite’s mounting system, hanging support system, and sequencing features help manage bad variability associated with changing installation conditions that naturally occur as a result of interfacing with other trades.

Finally, accidents create delays in the production system since project participants need to stop work flow to identify and remove the causes of accidents. As a result, increasing product and process safety helps project participants maintain continuous work flow. In this regard, Finelite’s pre-wiring, mated plugs and joining parts, and pre-lamping features create safer working conditions for fixture installers by simplifying and minimizing work required at the job-site.

### 4.6.2 – Reduce Inspection Times

Finelite’s ability to maintain tight tolerances allowed it to consistently achieve integer lengths. As a result, installers could easily check that fixtures aligned properly with the ceiling grid. Finelite also incorporated inspection into final assembly through the use of pre-wiring, mated plugs and joining, and pre-lamping. Consequently, factory workers automatically checked fixtures before shipping them out to customers.

### 4.6.3 – Reduce Rework Time

Again, Finelite introduced in-process inspection through the use of pre-wiring, mated plugs and joining, and pre-lamping. As a result, factory workers could immediately identify and fix defective work. Finelite also proactively reduced rework time by simplifying its products' design options. Narrowing its customers' choices in terms of color, fixture profile, and lengths helped limit potential mistakes when processing customer orders. This, in turn, helps reduce the need to perform rework.

Finelite's compromise of product variety in favor of faster order fulfillment allowed it to learn how to control its own work flow. Subsequently, Finelite has been regularly introducing new product families to appeal to new customers who may have felt limited by the previous product offerings.

### 4.6.4 – Control Work for Flow

Increasing process transparency helps project participants understand how to control work for flow. It helps them assess the state of the production system and adjust any production steps to ensure continuous work flow. Fixture fabricators that use aluminum for its fixtures had difficulty assessing the state of their orders because they represent only a small portion of business for aluminum extruders. In contrast, Finelite increased raw materials procurement transparency by using steel for its fixtures. With this business arrangement, Finelite became a primary client for its suppliers, so their suppliers had an incentive to deliver formed fixture profiles reliably to help Finelite achieve its 10-day lead time. Thus, Finelite had more control over its supply chain with the use of steel.

Finelite's Styrofoam packaging also increased process transparency by revealing which fixtures were left to install. Then, since the Styrofoam packaging allowed for out-of-sequence installation, the installer could plan for whatever installation sequence allowed for better work flow at the job-site.

### 4.6.5 – Reduce Processing Times

Finelite's reliability in achieving a 10-day lead time discourages speculative bulk buying from customers who are concerned about "getting their order into a backlogged production system." As a result, savvy customers can structure their orders into smaller process batches to match their installation schedules. Finelite also redesigned products and applied different technologies to help reduce processing times. With its suppliers, it worked out processes to roll steel sheets into fixture profiles. During final assembly, it installed a pre-wiring channel as well as mated plugs. In addition, the joining parts, on-grid mounting system, and leveling system further sped up job-site installation. Finally, Finelite reduced processing times by creating consistent interface conditions through its fixture features of integer lengths, mated plugs and joining parts, and the on-grid mounting system.

### 4.6.6 – Reduce Inventories

Ballard et al. (2001) identified "Reduce variability" as a technique for reducing inventories. This technique could be further clarified as "Reduce bad variability" to distinguish between bad variability as discussed in the "Structure Work for Flow" Section and good variability which is “a necessary implication of a business strategy” (Hopp and Spearman 2001, p. 288). Finelite’s decision to focus on limited product families, one shade of white, and integer lengths helped manage bad variability associated with changing product requirements in terms of fixture shape, color, and length. This modular approach also increased the likelihood that factory workers have already worked on a certain changeover between two specific products. As a result, they can use their previous experience to work on reducing the setup time between products.

Since production dies have already been made for the limited product families and the steel rolling process is relatively quick, steel suppliers did not need to fabricate fixture profiles in anticipation of orders from the fabricator. Instead, they could create fixture profiles quickly in response to fabricator orders so the production system can operate using pull.

### 4.6.7 – Reduce Time, Materials, and Information Spent Being Moved and not Processed

Finelite reduced the distances between the suppliers’ facilities and its own facilities by working with local steel suppliers. Finelite also increased the speed with which it transported fixtures by developing a method to palletize fixtures. Finally, its Styrofoam packaging allowed electricians to pull fixtures out from the middle of a stack, so they did not have to bother with removing the fixture above.

### 4.6.8 – Improve Supplier Quality and On-Time Delivery

Finelite’s decision to use steel instead of aluminum allowed it to form close alliances with a limited number of steel suppliers. By standardizing orders to their suppliers with its limited product families and its push for one shade of white, Finelite could actively learn with its suppliers from project to project and identify ways to improve the production process. Furthermore, Finelite’s commitment to a 10-day lead time provided guidance to its suppliers as to how they should establish their own production rates to match Finelite’s production rate.

### 4.6.9 – Improve Quality of Intermediate Products

Finelite’s fixture features of integer lengths, on-grid mounting system, hanging support system, and leveling system helped improve an electrical contractor’s ability to install fixtures as designed. Its pre-wiring and pre-lamping processes supported in-process inspection to prevent the passing of defective products further along the production process. In addition, Finelite’s efforts in packaging development to allow palletizing of fixtures helped protect products from breakage during transport.

### 4.6.10 – Increase Resource Productivity

Finelite increased utilization of its packaging by developing a process for retrieving used packaging from electrical contractors. It also increased resource fruitfulness by wrapping plastic around its pre-lamped fixtures so that the fixtures could be used during construction.

Finelite's new product development efforts helped it re-assign tasks to increase resource productivity in a couple ways. First, it transferred the task of painting fixtures normally performed by the fabricator to the supplier. This decision worked out well because most orders used the standard shade of white, so Finelite could focus instead on final assembly. Then, Finelite took on the tasks normally performed by the electrical contractor of wiring, forming of plug connections, and lamping fixtures. Finelite could take care of these tasks more efficiently because its factory conditions provided a more controlled environment in comparison to the job-site.

### 4.6.11 – Reduce Cost of Using Materials and Information

Finelite reduced material scrap by: (1) pre-wiring fixtures, (2) offering its hanging support system in 8 standard lengths so that an electrical contractor could pick a length that worked best with its project, and (3) recycling its used packaging. It reduced unneeded work space at the job-site through pre-wiring, use of its mounting system, pre-lamping, and sequencing support by its packaging. Finally, Finelite's decision to use steel for its fixtures instead of aluminum helped reduce emissions since steel has a lower amount of embodied energy in comparison to aluminum (Buchanan and Honey 1994).

### 4.6.12 – Reduce Cost of Acquiring Resources, Materials, and Information

Since Finelite offers a limited product line, the transaction of purchasing fixtures costs less since customers only need to pick a product line as opposed to developing its own unique fixture profile in coordination with the fixture fabricator. The use of a limited product line also helped reduce purchase prices since the fabricator can gain economies of scale from using the same production dies to fulfill additional orders. The use of steel and one shade of white also helped reduce purchase prices since steel is cheaper than aluminum and suppliers could purchase white paint in bulk.

### 4.6.13 – Understand, Critique, and Expand Customer Purposes

As mentioned in the “Increase Resource Productivity” Section, Finelite wrapped fixtures in plastic so that they could be used during construction. This allowed the fixtures to bring value to stakeholders during the pre-commissioning phase since project participants could then discontinue use of temporary lighting systems. Finelite’s mated plugs and joining parts also provided easier removal of fixtures for future operations and maintenance needs.

Finelite’s 10-day lead time helped push owners and architects to re-evaluate their desire for unique light fixtures. In particular, they had to decide if they prioritized speed versus aesthetics. If a primary purpose of the owner and architect was to complete the project quickly, then they should seriously consider using Finelite fixtures. However, if unique fixtures brought considerable value to the owner, then they should consider using products from other fixture fabricators.

Meanwhile, since it takes only half the number of indirect light fixtures to illuminate the same space as direct parabolic fixtures, the total-installed-cost for Finelite fixtures will be consistently less than direct parabolic fixtures (Finelite 2002). Thus, although electrical contractors may prefer Finelite’s installation advantages, they risk making less money with the use of Finelite fixtures if their profit is based on total-installed-cost.

### 4.6.14 – Structure Work for Value Generation

Finelite developed a niche for its products by redefining stakeholder interests. It helped electrical contractors see value in using fixtures that were easy to install and could be delivered reliably. Then, it helped owners and architects see value in using fixtures that could be purchased quickly. Once they saw how much sooner they could procure modular fixtures, they were more willing to forego their desire for unique light fixtures.

With these adjusted values in place, Finelite made sure its fixture features supported this new balance of stakeholder interests. Using steel fixtures, a push for one shade of white, limited product families, and commitment to a 10-day lead time, Finelite ensured reliable delivery soon after order completion. With integer lengths, pre-wiring, mated plugs and joining parts, the on-grid mounting system, the hanging support system, the leveling system, pre-lamping, packaging and palletizing, and sequencing, Finelite developed fixtures that were easier to install.

### 4.6.15 – Increase System Control

Finelite’s commitment to a 10-day lead time helped set production rates for all sub-assembly lines that fed into final assembly. Then, by viewing the overall production system, Finelite could identify when they should adjust different stage of production to make sure they maintained the 10-day lead time.

Finelite's standardized product offerings of one shade of white, limited product families, and integer fixture lengths helped to reduce production complexity. This allowed Finelite to increase its ability to increase system control because they had fewer parameters to manage, resulting in greater reliability in delivery and less waste during production. Then, they had the chance to learn from their mistakes and improve their ability to deliver products for similar orders.

Aluminum fixture fabricators' difficulty in clarifying the status of their orders with extruders created a difficult to manage the sub-assembly process in fixture fabrication. Thus, Finelite's switch to using steel to form limited product families increased system transparency because it formed alliances with nearby steel suppliers. These close relationships allowed Finelite to have a better gauge of the status of its orders with the steel suppliers. Then, it could adjust its own production system to process the incoming fixture profiles to reliably meet its 10-day lead time.

Ballard et al. (2001) identified "Reduce variability" as a technique for increasing system control. This technique could be redefined as "Increase good variability." As mentioned in the "Reduce Inventories" Section, good variability (e.g., "product variety, technological change, and demand variability") "can be a sound business strategy" if it "increases revenues by an amount that more than offsets the additional cost [of managing it]" (Hopp and Spearman 2001, p. 288). Finelite's decision to employ fewer product families and integer lengths introduced a manageable level of good variability into its production system in terms of fixture shape and length. This allowed it to prepare its production system for a predictable range of variability generated by customer orders. In addition, Finelite's decision to provide a hanging support system in 8 standard lengths introduced another facet of good variability based on potential customer orders.

## 4.7 – Expansion of Work Structuring Framework

Ballard et al.'s (2001) end-means hierarchies help project planning move "from a conception of production solely in terms of transformation of inputs to the Transformation-Flow-Value Generation concept of production advocated by Lauri Koskela." It is important to note, however, that the end-means hierarchies are not intended to be regarded as strict hierarchies as some techniques fall in different categories. Rather, the end-means hierarchies can be used to help promote lean thinking as companies think about Work Structuring principles and techniques.

Howell (2001, p. 16) represents Ballard et al.'s (2001) end-means hierarchies in a chart entitled "Business Objectives of Project-Based Producers" (Figure 48). Based on our earlier Work Structuring analysis, we make some recommendations for adjusting the chart to help expand the framework for Work Structuring, especially when a supplier-fabricator-installer relationship exists on a project. Each of the following sections explains new or modified Work Structuring techniques that fall under a specific higher-level Work Structuring principle. Figure 49 illustrates our recommendations in a revised chart. Bold boxes represent lower-level Work Structuring principles, and bold text indicates new or modified Work Structuring techniques.

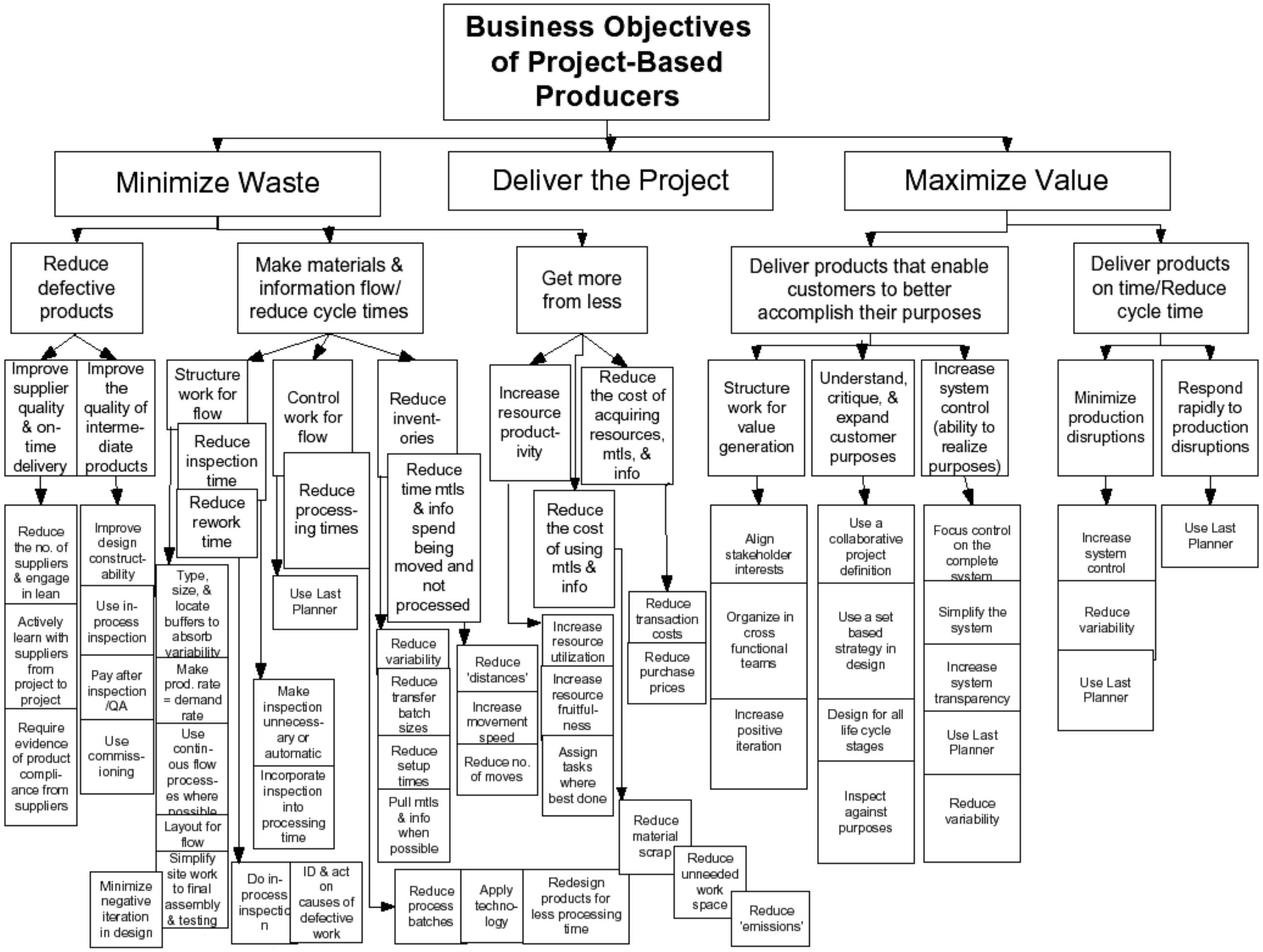

*Figure 48: Business Objectives of Project-Based Producers (Howell 2001)*

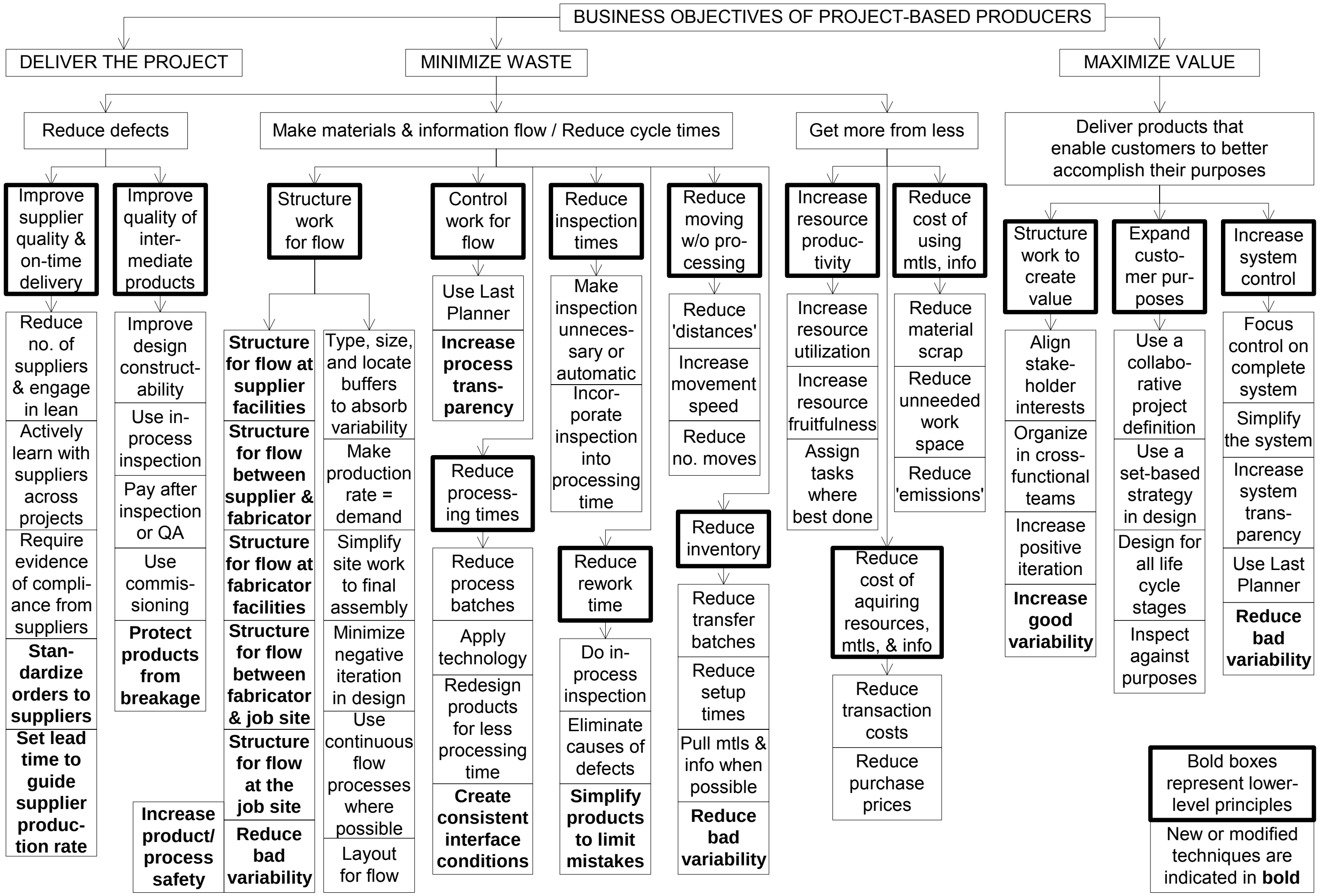

*Figure 49: Business Objectives of Project-Based Producers (adapted from Howell 2001)*

### 4.7.1 – Reduce Defective Products

Under “Improve supplier quality and on-time delivery”, we recommend adding the technique of “standardize orders to suppliers”. This helps suppliers anticipate future orders and organize their production systems accordingly. Under “Improve quality of intermediate products”, we suggest adding the technique of “protect products from breakage” to remind companies that product innovation should also consider alternative methods for packaging.

### 4.7.2 – Make Materials and Information Flow / Reduce Cycle Times

Under “Structure work for flow”, we suggest enhancing the techniques of “Use continuous flow processes where possible” and “Layout for flow” with the techniques of “Structure for flow at the supplier’s facilities”, “Structure for flow at the fabricator’s facilities”, and “Structure for flow at the job-site” to emphasize continuous work flow within a single facility. Then, we add the techniques of “Structure for flow between the supplier and the fabricator” and “Structure for flow between the fabricator and the job-site” to help project participants consider the rate at which work is released between different facilities.

Although “Structure for flow at the job-site” and “Simplify site work to final assembly and testing” are similar, they should remain separate because they represent complementary goals. “Structure for flow at the job-site” suggests that if work flow on the job-site is sporadic, efforts should be made to make work flow continuous. “Simplify site work to final assembly and testing” recommends minimizing raw materials processing on the job-site so that site work ideally manages only connection of pre-fabricated work chunks. Then, project participants can attempt to execute prefabrication work in parallel to help shorten overall project duration.

We list “Reduce bad variability” under “Structure work for flow” and “Reduce inventories” to distinguish between good and bad variability (Hopp and Spearman 2001, p. 288). We add “Increase product and process safety” under “Structure work for flow” because preventing accidents helps ensure continuous work flow. Similarly, we bring up the technique “Simplify products to limit potential mistakes” under “Reduce rework time” because rework happens, for example, when project participants make mistakes. As products become more complex (i.e., when they have more parts and more interdependencies), project participants are more likely to make a mistake. Thus, by simplifying products, project participants will have a better chance of performing work as required. This then reduces the potential for required rework.

Under “Control work for flow”, we add “Increase process transparency” since planners should develop a better assessment of production before attempting to adjust the production system to meet expected output. For example, as mentioned earlier, Finelite’s alliances with its nearby steel suppliers provided it with greater transparency of the status of work-in-progress (i.e., formed fixture profiles) in comparison to working with aluminum extruders. As a result, Finelite can either (1) adjust its production to match deliveries of work-in-progress from its suppliers, or (2) ask its suppliers to adjust their production rates to help Finelite improve its performance in fulfilling customer orders.

We recommend adding “Create consistent interface conditions” under “Reduce processing times” because installation problems often occur due to misfits. Developing consistant interfaces helps reduce fitting problems. In addition, installers can work more efficiently within familiar work environments, and this helps reduce processing times.

### 4.7.3 – Deliver Products that Enable Customers to Better Accomplish their Purposes

Under “Increase system control”, we recommend replacing the technique of “Reduce variability” with “Reduce bad variability” and adding “Increase good variability” under “Structure work to create value” to emphasize the obvious difference. Companies must strive to reduce bad variability to ensure value is delivered as promised. Meanwhile, increasing good variability helps companies structure their production systems to provide a pre-determined level of product customization in terms of aesthetics and performance. Consequently, by introducing good variability which can be managed by their production systems, companies will be able to generate additional value for their customers.

### 4.7.4 – Deliver Products on Time / Reduce Cycle Time Variation

We find the “Deliver products on time / reduce cycle time variation” section to be redundant with other sections of the ends-means hierarchy. The technique of “Increase system control” has been covered under “Deliver products that enable customers to better accomplish their purposes”. The technique of “Reduce variability” has already been expanded to the techniques of “Reduce bad variability” under “Minimize waste” and “Increase good variability” under “Maximize value.” Finally, “Use Last Planner” has already been addressed in “Control work for flow” and “Increase system control.” As a consequence, we recommend removing the “Deliver products on time / reduce cycle time variation” section to help streamline the chart.

## 4.8 – Case Study Conclusions

Finelite’s efforts in new product development and supply chain management generated an alternative lighting system that provided (1) better quality lighting in comparison to direct parabolic light fixtures and (2) fixtures that had lower total installation cost and could be procured and installed more quickly and reliably in comparison to direct parabolic and aluminum indirect light fixtures. By balancing the integration of product design with process design, Finelite chose to standardize fixture features that they felt could be compromised in favor of prompt order fulfillment and easier job-site installation.

As a result, within a competitive architectural lighting industry, Finelite created a niche market that allowed it to gain considerable market share during the economic boom of the 1990s since its standardized fixtures allowed San Francisco Bay Area Dot-com start-ups to quickly outfit their new and tenant improvement office spaces with indirect lighting systems. Thus, Case 2 demonstrated how a Work Structuring perspective effectively uncovered new opportunities for value generation in lighting system delivery.

However, if Finelite wishes to expand its enterprise, lean thinking suggests it should consider "three dimensions of perfection: (1) a uniquely custom product, (2) delivered instantly, with (3) nothing in stores" (Howell and Ballard 1998). A larger lighting company based in the UK adopted four complementary strategies to become both lean and agile in handling varying degrees of product variability and volume predictability (Aitken et al. 2002). As a result, the UK lighting company could more easily maintain its base market in the UK and increase its competitiveness in international markets.

Finelite's strategic decision to focus on a niche market was appropriate when it started as a new company. However, other fixture fabricators have since entered the standardized indirect light fixture market with competing products. If Finelite begins observing a decline in its niche market, it should consider additional lean and agile strategies to expand into new markets and maintain a competitive edge in the architectural lighting industry.

## 4.9 – Acknowledgments

This research was funded by grant SBR-9811052 from the National Science Foundation, whose support is gratefully acknowledged. Special thanks to Darrin Stone for introducing us to Finelite, and Terry Clark, founder and president of Finelite, for allowing us to conduct an in-depth study of his company. We would also like to thank Jan Elfving for assisting with data collection and processing of our interview with ALR. Finally, we wish to thank the following people for providing additional insight into the lighting industry:

*Table 17: Case 2 Acknowledgments*

| | |
|---|---|
| **Architectural Lighting Design** | David Malman |
| **Associated Lighting Representatives (ALR)** | Jim Elder |
| **David Malmgreen Design** | David Malmgreen |
| **Frank Electric** | Mike Jurewicz, Steve Harvey, John Stice, Victor Garcia, Frank Thomas, Wayne Wood, Eric Sullivan, B.J. Hanahcy, and Sotame Niualiku |
| **Horton Lees Brogden Lighting Design** | Lilian Rodriguez |
| **Lithonia Lighting** | Steve Odom |
| **Peerless Lighting** | Peter Ngai and Angela Lawrence |
| **Shaper Lighting** | Allen Reaves |
| **Taylor/Stokes Lighting** | Bob Stokes |
| **USS – POSCO Industries** | Susanne Setijadi |
| **Williams Lighting** | Roger Robertson |

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# CHAPTER 5 – STONE ON TRUSS CURTAIN WALLS

## 5.1 – Case Study Objectives

### 5.1.1 – Understand Current Work Structuring Practice

Case 3, the Stone on Truss Curtain Walls case study, follows the product development process for an engineered to order (ETO) product. Since Case 1 examined made to stock (MTS) and fabricated to order (FTO) products and Case 2 examined assembled to order (ATO) products, we chose to focus on an ETO product for Case 3 to further demonstrate the applicability of Work Structuring. In particular, we wanted to investigate Work Structuring issues within a more complex environment. Curtain wall building enclosure systems provided an ideal case in this regard because they:

- Require involvement of many companies representing different areas of expertise during design development.
- Offer multiple options in terms of materials procurement, fabrication techniques, and installation strategies.
- Impact overall building aesthetics as well as performance of different building systems including structural, mechanical, and lighting systems.

Unlike Case 2 which focused on one company’s efforts to provide an alternative Work Structure, Case 3 explores how multiple companies may resolve Work Structuring issues during the course of curtain wall development.

### 5.1.2 – Develop Methodology for Work Structuring Practice

In this chapter we experiment with ways to identify and make transparent Work Structuring issues that emerge during periodic design collaboration meetings. Design collaboration involves: (1) the elucidation of a design question, (2) the development of potential, alternative solutions, (3) an assessment of their value to the project (e.g., impact on company and personal values of stakeholders), (4) a negotiation between project participants to single out preferred solutions, (5) a decision to pursue a particular solution, and (6) the incorporation of the solution into the overall design. If the solution changes project scope, the owner will likely allow the change if it improves overall project value (e.g., performance in terms of budget, schedule, quality, or safety). However, a tension exists between decision delays allowing more time for discovering or developing better solutions and procurement constraints creating pressures in production scheduling. Thus, we will investigate how to improve the alignment between the decision-making process and the fabricator's production process.

## 5.2 – Company and Project Background

Walters & Wolf, one of the largest curtain wall specialty contractors in the United States (ENR 2004), provided access to one of its on-going projects for Case 3. Prior to our research, John Fulton, president of the glass division, hosted field trips to Walters & Wolf's manufacturing facilities in Fremont, California, for graduate-level architecture courses in prefabrication and curtain walls.

To assist our research, Mr. Fulton invited us to attend collaboration meetings for a retrofit project located in the peninsula region of the Bay Area. We observed that important decisions could not be addressed during meetings in absence of an owner's representative. As a result, this project experienced delays in design development, so Mr. Fulton recommended trying a different project for our case study.

This experience alone provided insight into Work Structuring practice. Those who are authorized to make design decisions should be regarded as resources that can either assist or hinder design development and fabrication. Thus, *how* and *when* they should respond to design development questions should be outlined to help other project participants structure their work accordingly. For example, design decisions could be prioritized based on whether they should be addressed and resolved specifically during collaboration meetings or through the use of responses to requests for information (RFIs).

Mr. Fulton then introduced us to a project which he felt demonstrated genuine collaboration by all project participants. The J. David Gladstone Institutes project developed a $74 million 17,700 $m^2$ (190,000 $ft^2$) research building within a private biotechnology complex across the street from the 43-acre Mission Bay campus of the University of California, San Francisco (UCSF) (Perry 2003, Gladstone 2005). Upon attending one of Gladstone's design collaboration meetings, we observed a high degree of interaction between project participants, including an owner's representative. Thus, we decided to focus Case 3 on this project and specifically investigated Gladstone's development of the stone on truss curtain wall portion of its $6.6 million building enclosure system (Figure 50).

*Figure 50: J. David Gladstone Institutes at the Mission Bay campus of UCSF (from Gladstone 2005) (Stone on truss curtain wall indicated by outlined region)*

## 5.3 – Methodology for Data Collection and Processing

We collected data for Case 3 from December 2002 to February 2003 during 6 design coordination meetings that focused on Gladstone's curtain wall development. At the meetings, we observed the interaction between Gladstone's owner representative, architect, structural engineer, general contractor, and curtain wall fabricator (Table 18). Throughout our study, project participants usually met at the architect's office in San Francisco, California. On January 21st, only 2 architects showed up at the meeting because their office was preparing the release of 100% shell and core drawings for bidding 12 trades. On February 12th, they held the meeting at the fabricator's facilities in Fremont, California, to observe finishes on large stone samples.

*Table 18: Number of Attendees at each Coordination Meeting*

| **Meeting Date** | **Dec 17** | **Jan 14** | **Jan 21** | **Jan 28** | **Feb 12** | **Feb 25** |
|---|---|---|---|---|---|---|
| Owner Representative | 1 | 1 | 1 | 1 | 2 | 0 |
| Architect | 5 | 4 | 2 | 4 | 5 | 3 |
| Structural Engineer | 1 | 0 | 0 | 0 | 0 | 0 |
| General Contractor | 2 | 2 | 1 | 1 | 1 | 1 |
| Curtain Wall Fabricator | 6 | 4 | 4 | 8 | 8 | 6 |
| *Total* | *15* | *11* | *8* | *14* | *16* | *10* |

To overcome a learning curve pertaining to the intricacies of curtain wall design, the researcher took handwritten notes to capture each meeting's dialogue. We also considered using a video camera, audio recorder, or laptop computer, but decided they might be disruptive and their presence might curtail normal behavior. Taking handwritten notes allowed the researcher to blend in more easily in the meetings and observe standard interchange and discourse between project participants. Whenever possible, we also separately documented personal interpretations of meeting dynamics.

The researcher usually sat next to junior personnel, outside of the primary meeting circle. This allowed the researcher to occasionally clarify discussion ambiguities with junior personnel during meetings. Thus, we avoided interrupting intensive meeting conversations that dealt with major design issues.

After meetings held at the architect's office, the researcher accompanied junior personnel from the curtain wall fabricator part way as they returned to their office on public transportation. During these times, they provided additional insight into and clarification of various meeting issues. We also followed up with them by phone to get further clarification of the curtain wall fabricator's perspective.

In transcribing meeting notes, we noted only what was written and avoided adding layers of interpretation. However, we corrected transcription errors regarding company affiliation in the first few meetings when we later understood the roles of different meeting participants. In addition, if possible, we identified the subject of discussion when a meeting dialogue referred to an ambiguous “it” or “that”. The curtain wall fabricator also supplied a set of shop drawings and progress schedules to assist us in our analysis.

We began processing data by developing tables that chronologically note design issues as they emerged during meetings. We assigned tracking codes to each issue to identify when they re-emerged in subsequent meetings. Then, we created a process map measuring 3 sheets of 8.5” x 11” paper by 7 sheets across to capture the complexity of curtain wall design, fabrication, and installation. We include portions of this process map in later sections of this chapter. We also augmented our analysis with references that explain in detail various aspects of curtain wall production.

## 5.4 – Curtain Wall Industry Background

### 5.4.1 – Introduction

A curtain wall is “an exterior wall supported wholly by the structural frame of a building and carrying no loads other than its own weight and wind loads” (Ching 1995). Buildings can contain one or several different curtain wall systems. Walters & Wolf can design, fabricate, and install the following types of curtain walls (Walters & Wolf 2004): (1) architectural precast concrete panel systems, (2) glass fiber reinforced concrete (GFRC) panel systems, (3) natural stone panel systems, (4) stone on truss frame panel systems, and (5) structural glass wall systems. Gladstone’s stone on truss frame panel system combines stone panels, insulating glass units, and aluminum extrusions on steel trusses.

### 5.4.2 – Supply Chain Map

The supply chain for a stone on truss curtain wall typically involves companies or organizations that take on the role of owner, architect, structural engineer, general contractor, curtain wall installer, curtain wall fabricator, steel truss fabricator, stone fabricator, glass fabricator, aluminum extruder, steel supplier, stone quarry, float glass supplier, aluminum extrusion die fabricator, and aluminum billet supplier. Some companies or organizations may take on several of these roles.

Figure 51 maps Gladstone’s supply chain for the stone on truss curtain wall. It details contractual relationships between parties, site access during construction, communication beyond what is required due to contractual relationships, and flows of goods between project participants. Dashed boxes indicate work performed by a single company.

### 5.4.3 – Contractual Relationships

On Gladstone, preconstruction began in June 2001, design in May 2002, and construction in March 2003 (Gladstone 2005). When we started our study in December 2002, Gladstone already held contracts with (1) a company that served as the owner’s representative – Mezzatesta Sklar Architects of San Francisco, California (2) an architect – NBBJ of San Francisco, California, and (3) a general contractor – Rudolph and Sletten of Redwood City, California. Walters & Wolf started assisting with curtain wall design development in Fall 2002, and they received a letter of intent / notice to proceed in January 2003. We attended collaboration meetings until February 2003, and Walters & Wolf submitted shop drawings and structural calculations for approval in May 2003. Eventually, construction completed in September 2004.

For curtain wall development, the architect is responsible for developing how the curtain wall appears on the exterior of the building. The architect held a contract with the structural engineer – Rutherford & Chekene of Oakland, California. The structural engineer was responsible for ensuring that the building would structurally support the emerging curtain wall design.

The general contractor held contracts with 73 subcontractors on Gladstone (Gladstone 2005), including a contract with Walters & Wolf for curtain wall fabrication and installation. Prior to fabrication, the curtain wall fabricator is responsible for developing all facets of the curtain wall so that it will achieve and support the exterior appearance as defined by the architect.

On Gladstone, the curtain wall fabricator chose to fabricate the steel trusses. On other projects, based on factory capacity, they may decide to subcontract steel truss fabrication. Regardless, the steel truss fabricator procures raw materials from a steel supplier.

The curtain wall fabricator contracted with the stone fabricator, Campolonghi Italia S.r.l. of Montignoso, Italy; they had worked together successfully on previous projects. The stone fabricator held contracts with various quarries to supply different stone types, and accordingly they provided to the owner and architect small samples from its supplying quarries to assist with stone type selection. Later, the stone fabricator provided larger samples to assist with stone finish selection.

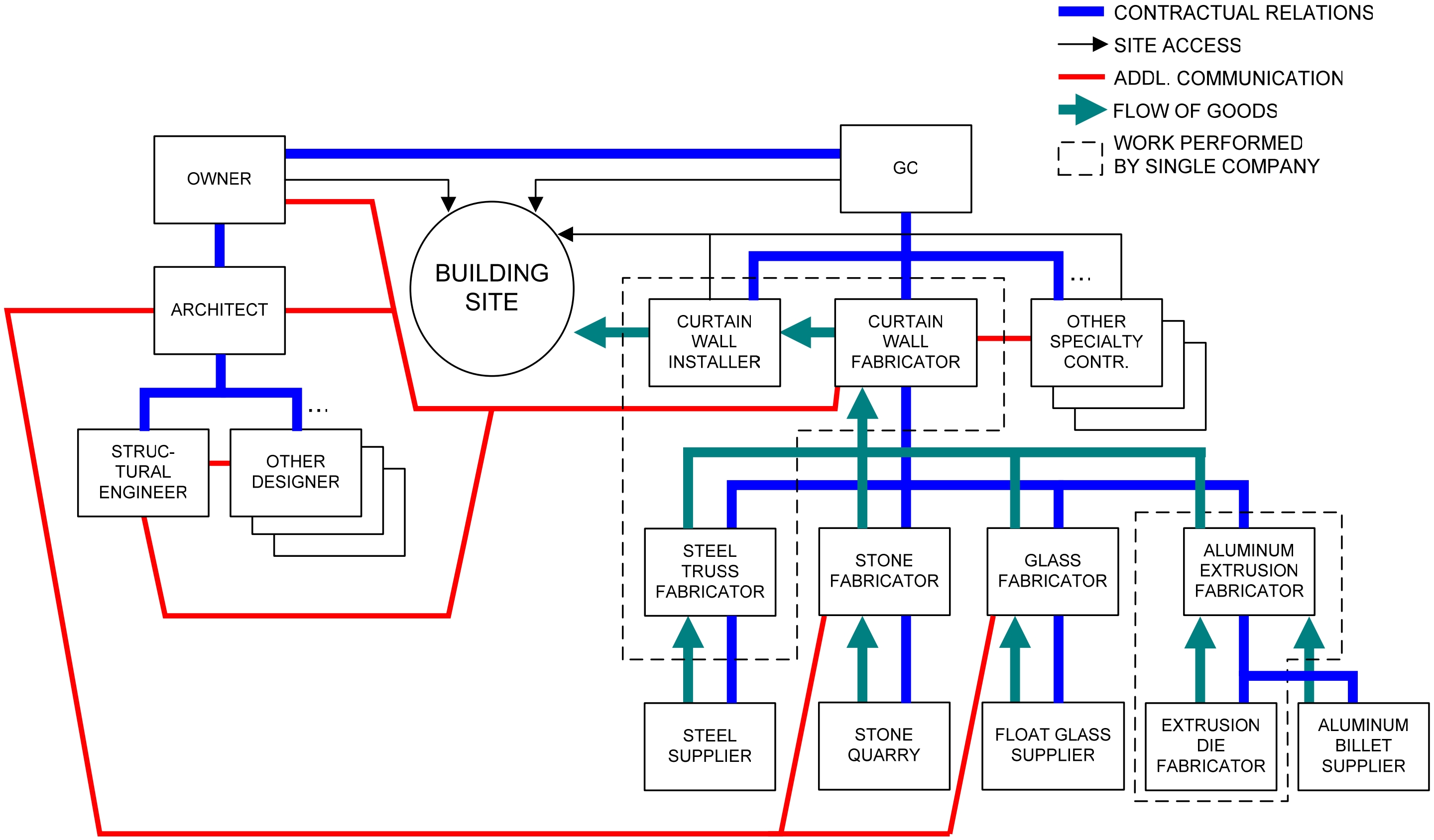

*Figure 51: Supply Chain for Gladstone's Stone on Truss Curtain Wall*

The curtain wall fabricator signed a contract with the glass fabricator, Viracon, Inc. of Owatonna, Minnesota. If the general contractor had signed on a glass and glazing contractor, then the glass fabricator would have needed to work under the glass and glazing contractor instead. The owner and architect selected the design (e.g., glass type and finishes) for insulating glass units based on samples provided by the glass fabricator. The glass fabricator procures its raw materials from a float glass supplier.

The curtain wall fabricator also signed a contract with an aluminum extruder. To run extrusions, the extruder must get dies fabricated in-house or contract the work out to a die fabricator. On Gladstone, the extruder fabricated dies in-house and procured raw materials from an aluminum billet supplier. In terms of extrusion design, the architect specified the outward appearance of extrusions, the curtain wall fabricator designed the extrusion profiles to achieve the outward appearance requested by the architect, and the extruder provided samples to assist with color selection by the owner and architect.

### 5.4.4 – Work Structuring Insight from Contractual Relationships

Work Structuring determines *who* is best suited to perform required work chunks. Figure 51 reflects meeting observations and illustrates how the curtain wall fabricator and aluminum extruder on Gladstone took on roles that in other circumstances could be performed by other companies. By clarifying project roles on a supply chain map at the beginning of a project, planners might uncover better strategies for structuring and allocating work based on availability and skill set of potential project participants.

Work Structuring also determines *when* and in *what* capacity should project participants begin project involvement. Sometimes, companies may not receive official contracts representing their work until months after becoming involved in the project. Within that time frame, these companies may assist with design development to increase the likelihood of being awarded the contract for fabrication or installation. Unfortunately, if companies perform pre-contract design assistance on a volunteer basis as Walters & Wolf did in Case 3, they run the risk that the general contractor will select another company to execute the work. Since the general contractor is legally allowed to do this, practitioners have indicated that this has happened on past projects.

Owners may feel such an arrangement helps them get the best work out of potential project participants. However, companies that remain anxious about their project status may provide inconsistent advice since they are trying to do whatever it takes to get the fabrication or installation job, and this may conflict with what generates more value for owners. Recent research has suggested the use of target costing to provide a more equitable working situation for project participants that assist with design development (Ballard and Reiser 2004). With this approach, primary specialty contractors were "brought on board prior to the completion of schematic design and participated in its final stage" to help determine how to meet or beat target costs established by the owner. Thus, such an arrangement may allow for better Work Structuring and generate more value for the owner. Then, we can begin to understand how different working environments allows project participants to be able (or unable) to influence major Work Structuring decisions.

An interesting question to consider is to what extent do alternative Work Structures in the form of supply chains exist before any specific project begins? That is, does the structure of supply chains establish Work Structuring options? For example, for stone on truss curtain walls, how many companies are capable of fulfilling each of the major roles identified in Figure 51? To what extent have companies established the boundaries of their role in the stone on truss curtain wall supply chain? If companies have established distinct roles and handoffs of work between these roles, then the supply chain has taken care of a considerable portion of Work Structuring, and projects need to simply decide on the combination of companies they want to involve on their project. However, if companies blur the lines between roles and handoffs of work between roles so that they can market themselves to a variety of project situations, then the burden of Work Structuring falls upon projects as they need to (1) determine project-specific roles and handoffs of work between these roles and (2) select a combination of companies to take care of the project-specific roles. Thus, future research might investigate how to determine the extent of Work Structuring managed by the structure of supply chains.

### 5.4.5 – Flows of Information

Figure 52 illustrates the flows of information and materials (i.e., product samples) during curtain wall design development. The owner first explains its expectations to help guide the architect in developing an initial exterior appearance for the curtain wall. At this stage, the architect obtains product samples from potential fabricators to help with preliminary curtain wall design decisions such as selecting the stone type. The curtain wall fabricator then develops the design of curtain wall components to support the architect’s vision. During this stage, the architect and curtain wall fabricator exchange information regularly to guide each other’s work. The architect also reviews with the owner detailed product samples provided by fabricators to refine specific design decisions such as glass coatings.

The structural engineer reviews the developing curtain wall design to make sure it can be supported by the structural frame. Once the curtain wall fabricator has all information needed to proceed with fabrication, the design is complete. The curtain wall fabricator publishes the final design in the form of shop drawings and submits them for approval by the architect. Then, after approving the shop drawings, the architect incorporates the curtain wall design into the overall building design.

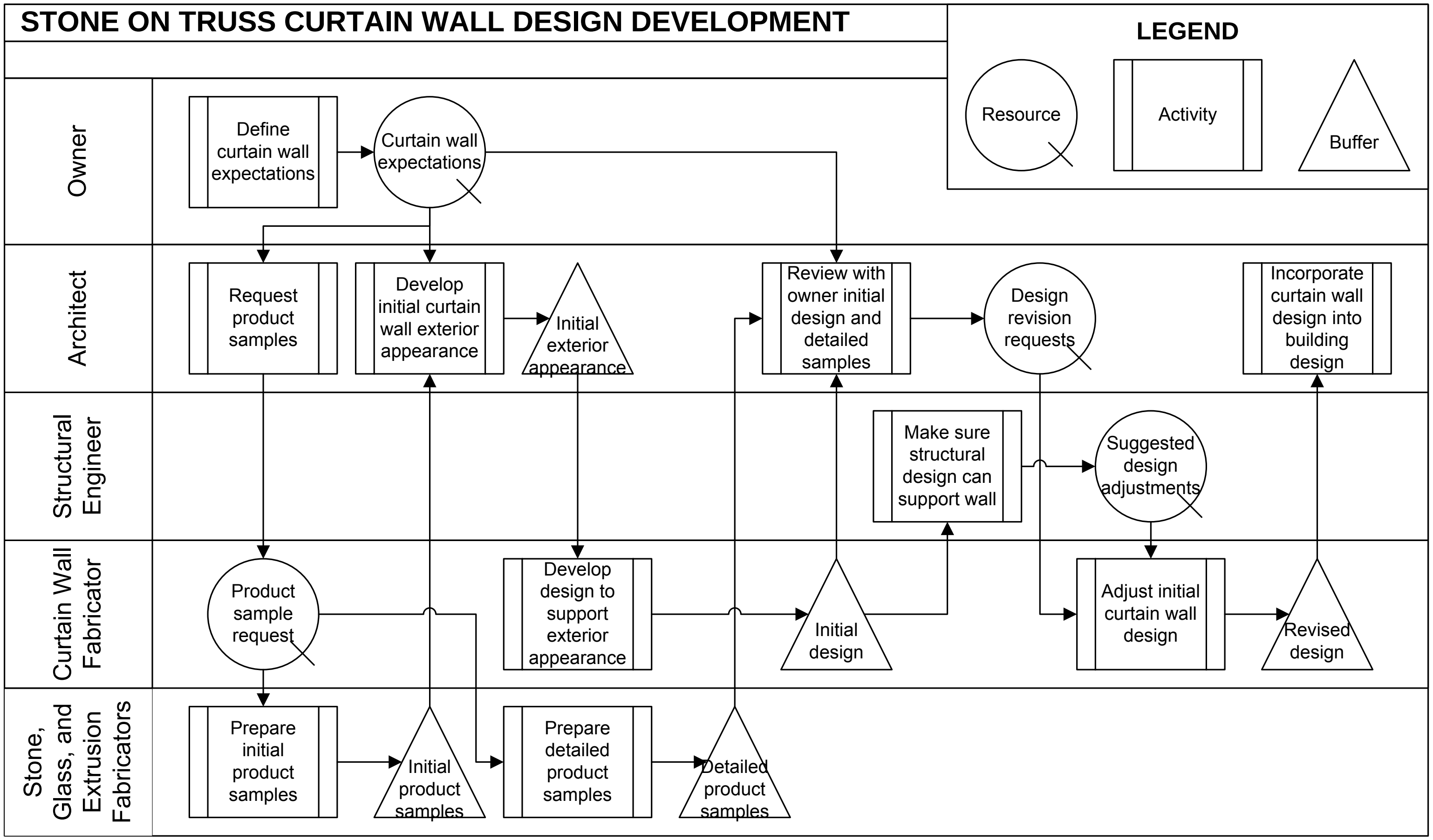

Figure 52: Stone on Truss Curtain Wall Design Development

## 5.4.6 – Flows of Goods

The curtain wall fabricator procures common-sized members from local steel suppliers to form the steel trusses. The stone fabricator has long-term relationships with quarries in different countries for supplying stone. The glass fabricator forms insulating glass units after procuring common glass types from local float glass suppliers and patented glass types from specialty suppliers. The aluminum extruder either procures aluminum billets from a separate supplier or dedicates a separate company branch to forming billets.

The curtain wall fabricator combines the steel truss, stone panels, insulating glass units, and aluminum extrusions to form the stone on truss curtain wall units (Figure 53). Then, the units are delivered to the building site and lifted into place.

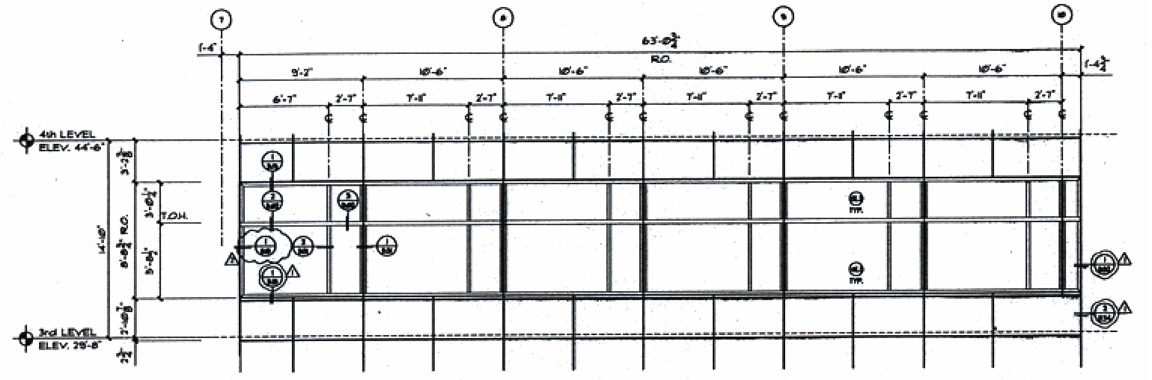

*Figure 53: Shop Drawing of Punched Window Wall containing Stone Panels, Insulating Glass Units, and Aluminum Extrusions (Walters & Wolf 2003)*

## 5.4.7 – Customer Requirements

Although the curtain wall fabricator holds a contract only with the general contractor, it regularly responds to inquiries and requests by the owner and architect because: (1) The owner can authorize scope changes if the associated costs or savings might generate additional value for (or reduce waste on) the project, and (2) The architect's aesthetic requirements can impact the level of skills and resources required for production, so the curtain wall fabricator must keep the architect informed of fabrication and installation limitations. However, if the contract with the general contractor does not include wording to promote overall value generation, the curtain wall fabricator may not reveal ways to improve the overall project if it somehow negatively impacts general contractor work.

## 5.5 – Analysis of Product-Process Design Integration

### 5.5.1 – Stone on Truss Curtain Wall Overview

Gladstone's stone on truss curtain walls consisted of steel trusses, stone panels, insulating glass units, and aluminum extrusions with units up to 9.2 m (30 ft) in length and 3.0 m (10 ft) in height. Stone on truss curtain walls are complex because they combine materials with different physical properties and varying sourcing and procurement lead times. In particular, Case 3 examines design development and fabrication for the skin components of the curtain walls (i.e., stone panels and insulating glass units) to understand how project participants managed integration of product and process design. We focus on skin components because, compared to the curtain wall's supporting components of steel trusses and aluminum extrusions, they required more feedback from the stone and glass fabricators during design development.

### 5.5.2 – Location of Stone on Truss Curtain Walls

Curtain walls can be classified as "stick" or "unitized" systems (Ching 1995, Minkoff 2000):

- **Stick system** – a curtain wall system in which structural framing components are assembled piece by piece at the job-site, to frame vision glass and spandrel units.
- **Unitized system** – a curtain wall system in which structural framing components are pre-assembled in a shop facility, to frame vision glass and spandrel units. Unitized curtain walls are typically one story tall, pre-assemble skin and supporting components into combined units, ship as combined units to the job-site for installation, and may be pre-glazed or glazed after installation.

Project participants need to decide which parts of a building will be enclosed with stick versus unitized systems. Since stick systems are handset at the job-site, they can more easily conform to uneven building profiles. As a result, stick systems can appear more integrated due to the lack of prominent joints between pre-assembled units. In contrast, while unitized systems such as stone on truss curtain walls can combine the aesthetic benefits of using higher quality materials (e.g., natural stone as opposed to GFRC) with the benefits of off-site pre-fabrication, it may be difficult to conceal joints between pre-assembled units, thus compromising the aesthetic goal of uniformity across a building envelope. Unitized systems also require special lifting equipment for job-site installation. However, a benefit of using unitized systems is that they may handle seismic loading, which is a primary concern in California, better than stick systems (Minkoff 2000).

Project participants decided to use a unitized, stone on truss curtain wall system along the longer sides of the 3rd, 4th, and 5th floors (Figure 50) because of Gladstone's rectangular footprint and the following building features (Oshiro 2003) (Figure 54):

- Areas for building operations and administration on the 1st floor.
- Open space that can be leased to future tenants on the 2nd floor.
- Laboratory, support, and office space on the 3rd, 4th, and 5th floors.
- An animal facility on the 6th floor.
- A mechanical penthouse on the roof.

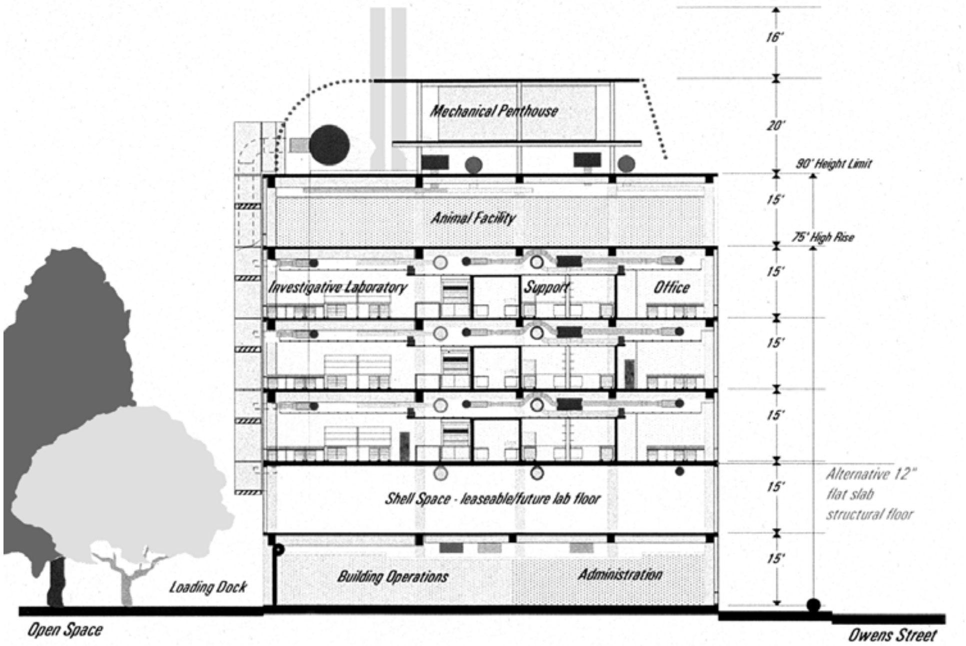

*Figure 54: Floor-by-Floor Schematic of Gladstone (image by NBBJ, from Oshiro 2005)*

Using a unitized system of stone on truss curtain walls helped introduce a consistent appearance that highlighted the primary research floors. Thus, unitized systems work well in covering large, repeating areas.

In contrast, owners often use stick systems on lower floors since unitized systems with visible joints may be perceived as lower quality by pedestrians and street traffic. Stick systems can also more easily conform to the varying conditions surrounding each entranceway. Thus, Gladstone used a stick system on the 1st and 2nd floors.

### 5.5.3 – Stone Type and Inherent Imperfections

The architect originally planned to use limestone on Gladstone because of its aesthetic traits. However, the owner decided to use granite that mimicked limestone because it was a less expensive option. After the curtain wall fabricator joined the project, they suggested using a stone fabricator that they had worked with in the past. The recommended stone fabricator sent 30.5 cm x 30.5 cm (12” x 12”) stone samples from their supplying quarries to Gladstone. The owner and architect reviewed the samples and indicated their acceptance of the stone fabricator’s involvement on Gladstone by narrowing their selection to three stone types among those sent.

Then, the owner and architect reviewed the imperfections associated with each stone type because of the direct impact they have on order amount and cost. Consistent stone types with fewer imperfections cost more to procure. Stone types that contain large veins or calcinations are difficult to work with because the imperfections might result in only 50% of surface area being usable. Thus, using imperfect stone may require the purchase of additional stone to make up for the imperfections. Alternatively, imperfect stone could be used on higher floors where the imperfections would be hard to detect from the street.

After reviewing feedback from the curtain wall fabricator, the owner and architect narrowed their selection to Conquistador Dorato granite (Gladstone 2005). When the curtain wall fabricator informed the stone fabricator of the stone type decision, the stone fabricator began retrieving the corresponding quarry blocks from their stockyard (Figure 55) to prepare for production. Figure 56 illustrates the process for stone selection.

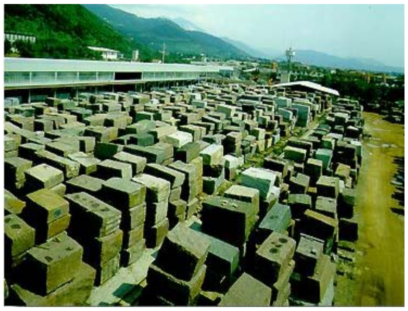

*Figure 55: Quarry Block Stockyard (Campolonghi 2004)*

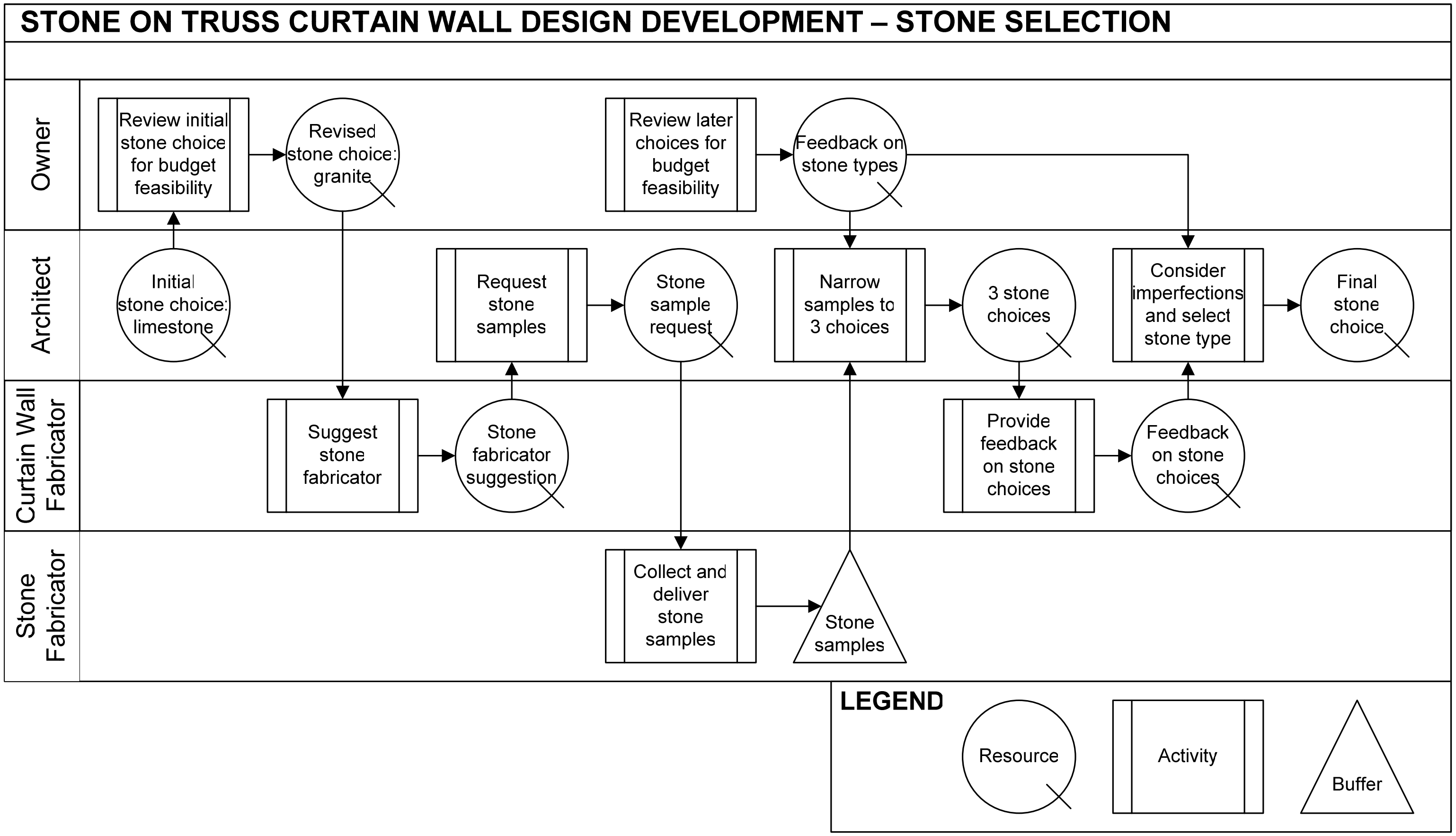

*Figure 56: Design Process for Stone Selection*

### 5.5.4 – Allowable Range of Stone Imperfections

The owner and architect joined the curtain wall fabricator on a visit to the stone fabricator’s facilities to finalize various stone design decisions. One design decision during this “Stone Trip” was to define the allowable range of imperfections. In preparation for Gladstone’s Stone Trip, the stone fabricator cut single slabs from 6 to 10 blocks of Conquistador Dorato granite. During their visit, the owner and architect reviewed these samples and pointed out any imperfections that should be removed from the slabs during fabrication. In particular, they identified sporadic black spots as an imperfection and requested that none of the panels contain black spots larger than an American quarter (about 24.3 mm or 0.96” in diameter). Then, they selected 3 to 7 samples to represent the allowable range of imperfections. Figure 57 illustrates the design process for the allowable range of stone imperfections.

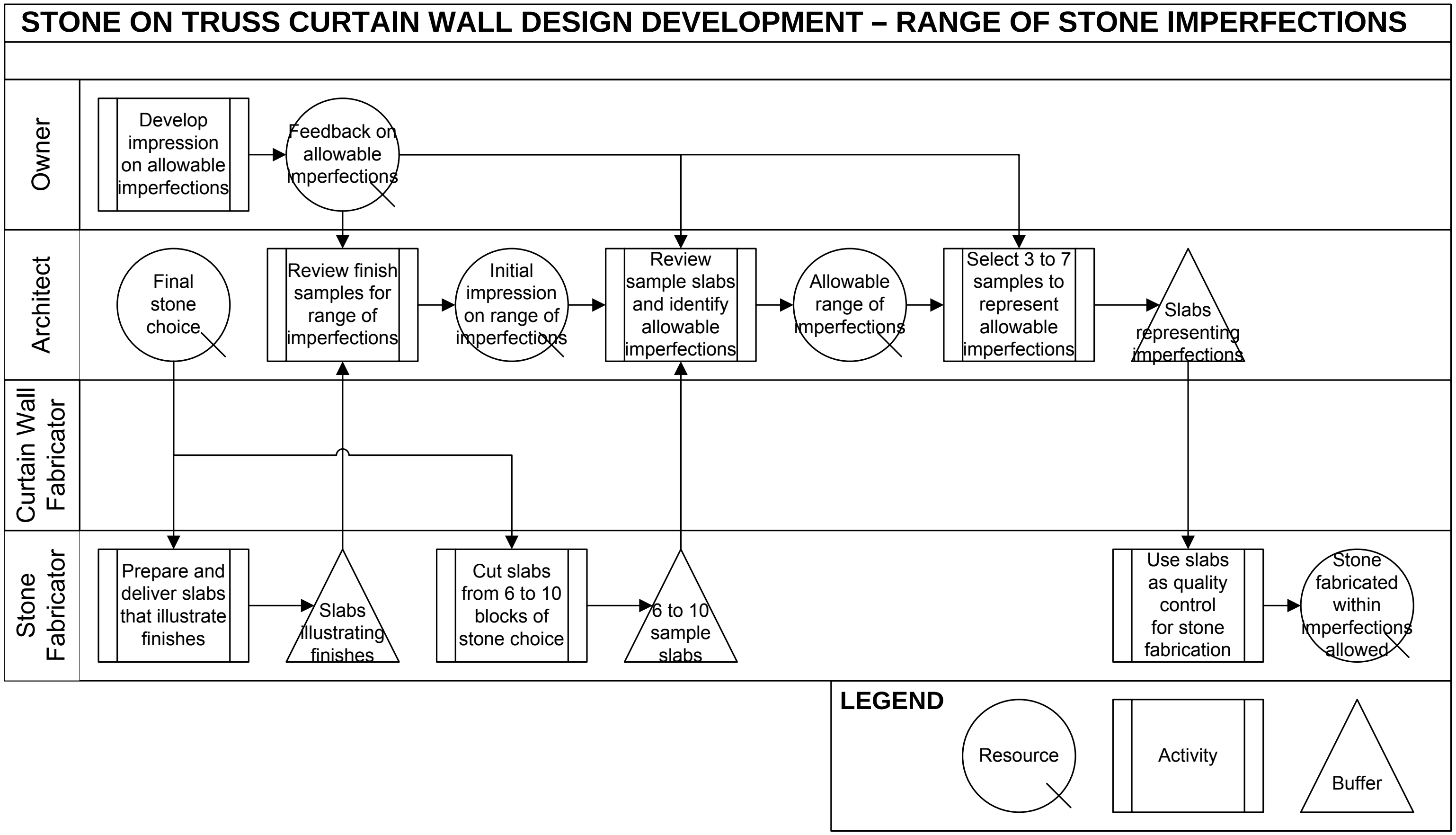

*Figure 57: Design Process for Allowable Range of Stone Imperfections*

### 5.5.5 – Forming Stone Panels

The stone fabricator can begin the slabbing process after project participants decide on both panel thicknesses and sizes. To determine panel thicknesses, project participants have to resolve the following conflicting objectives:

- Thinner panels increase the number of slabs that can be cut from each block.
- Thinner panels reduce the weight of each piece. This reduces the loads applied by the curtain wall on the structural frame. It also allows for easier handling.
- Thicker panels help prevent breakage during shipping and handling.

Based on experience from previous projects, the curtain wall fabricator decided on a stone panel thickness of 3.0 cm (1.2”) for the stone on truss curtain walls.

The stone fabricator used diamond disks (Figure 58) to cut quarry blocks into smaller, more manageable blocks. Diamond disks can cut approximately 2.3 $m^2$ (25 $ft^2$) of granite per hour (Elberton 1997). Then, they used diamond wires to square the smaller blocks to improve the fit into gang saws (Figure 59). Next, they transferred the blocks to the gang saw factory (Figure 60). Gang saws then cut the blocks into thin slabs according to the required panel thickness (Figure 61).

Figure 58: Diamond Disk
(Campolonghi 2004)

Figure 59: Block-Squaring
by Diamond Wire
(Campolonghi 2004)

Figure 60: Staging Blocks before Gang Saw
(Campolonghi 2004)

Figure 61: Gang Saw Factory
(Campolonghi 2004)

Although both diamond wires and gang saws can cut panels to specified thicknesses, they differ in operating costs and cutting speed:

Table 19: Diamond Wires vs. Gang Saws (based on Graniteland 2005)

| | **Operating Costs** | **Cutting Speed** |
|---|---|---|
| *Diamond Wires* | \$10 per $m^2$ (\$0.93 per $ft^2$) | 100 cm per hr (39.4” per hr) |
| *Gang Saws* | \$1.78 per $m^2$ (\$0.17 per $ft^2$) | 5 cm per hr (2.0” per hr) |

Since diamond wires are more expensive to operate, the stone fabricator limits their use to: (1) squaring blocks for gang saws, (2) low volume orders, (3) orders requiring shorter lead times, (4) orders involving more expensive stone, or (5) orders containing panels with many different thicknesses (Graniteland 2005). Since gang saws may require up to 2.5 days to cut one load, they are more appropriate for: (1) high volume orders of panels with the same thickness, (2) orders that can accommodate longer lead times, or (3) orders involving less expensive stone.

Once slabbing is complete, the fabricator cuts the required panel sizes using a multi-disk cutter while accounting for the allowable range of imperfections (Figure 62).

*Figure 62: Multi-Disk Cutter (Campolonghi 2005)*

### 5.5.6 – Stone Panel Sizing and Truss Design

Based on the expertise of the architect and curtain wall fabricator, curtain wall design and joint design can be executed by different project participants (Table 20). Joint design, in effect, determines stone panel sizes and vice versa. The architect and curtain wall fabricator typically negotiate joint locations since the architect may wish to limit the number of joints as an aesthetic goal while the curtain wall fabricator needs to manage structural design, stone fabrication, and curtain wall fabrication, delivery, and installation limitations. The structural engineer may also provide feedback to help guide the design.

*Table 20: Handoffs of Joint Design*

| **Architect** | **Curtain Wall Fabricator** |
|---|---|
| Architect designs curtain wall but does not specify joint locations. | Fabricator accepts curtain wall design and determines joint locations. |
| Architect designs curtain wall and indicates preferred joint locations to create larger panels. | Fabricator redesigns more feasible joint locations to create smaller panels. |
| Architect designs curtain wall and indicates feasible joint locations. | Fabricator produces curtain wall according to architect's curtain wall and joint designs. |

If panels are large, the curtain wall fabricator may try to break panels into two or more smaller units in order to increase the number of anchor points and improve distribution of dead load across the building's structural system (Figure 63). Theoretically, the curtain wall fabricator can achieve almost any jointing condition, but cost is a limiting factor.

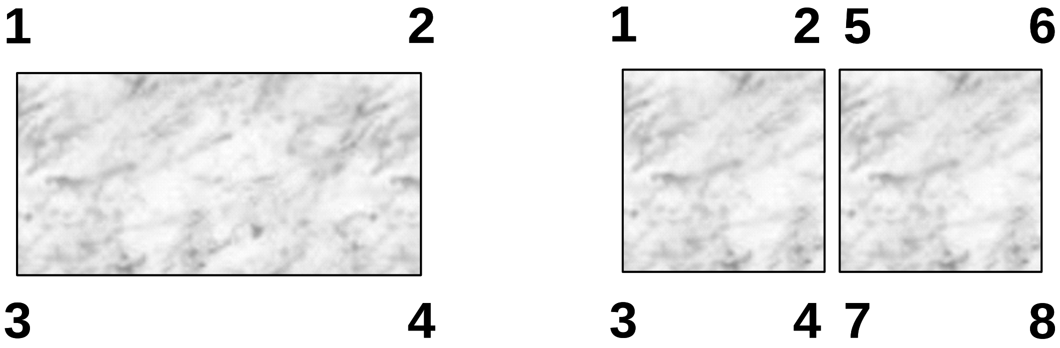

*Figure 63: Four versus Eight Anchor Points for the Same Surface Area*

On Gladstone, the stone design called for 315 panels with 117 different sizes. The architect used 40 to 50 of these sizes repeatedly throughout the building. This range of variability in panel sizes represents a less complicated job for the curtain wall fabricator (to put this in perspective: another recent project called for the fabricator to make 271 panels with 241 different sizes to enclose an unusually-shaped building). However, most panels in the section that we studied for Case 3 (Figure 50) were approximately 0.9 m x 1.5 m (3' x 5') in size.

With initial panel sizes and thicknesses, the curtain wall fabricator then designs steel trusses to support all curtain wall components. The curtain wall fabricator submits the initial truss design to the structural engineer for review. If the structural engineer determines that the structural frame cannot reasonably support the curtain wall loads, the curtain wall fabricator will need to modify the steel truss design and panel sizes until curtain wall loads can be supported.

Once the truss design and panel sizes are finalized, the curtain wall fabricator can initiate truss fabrication and the stone fabricator can begin cutting required panel sizes. Figure 64 illustrates the design process for panel sizing and truss design.

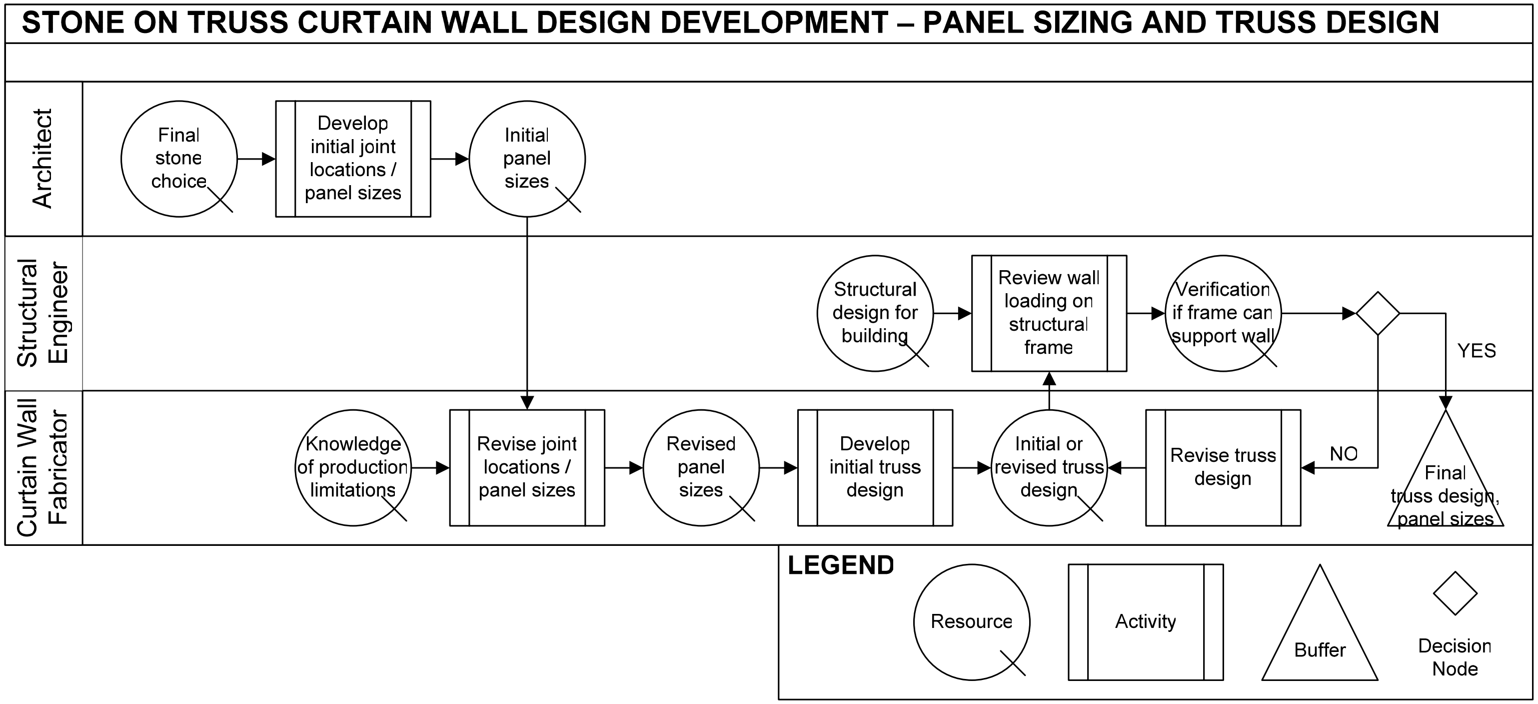

*Figure 64: Design Process for Panel Sizing and Truss Design*

### 5.5.7 – Stone Penetration Location and Sizing

Drilling penetrations in stone panels is risky because panels can break. This risk is reduced with the use of better equipment. On Gladstone, the stone fabricator had better drilling equipment than the curtain wall fabricator (Figure 65). Thus, the Last Responsible Moment for the architect to decide on penetrations would be a function of the time it takes for:

- The stone fabricator to:
  (1) Drill penetrations in panels.
  (2) Finish remaining stone fabrication steps.
  (3) Transport panels from Italy to the curtain wall fabricator in California.
- The curtain wall fabricator to:
  (1) Fabricate the curtain walls.
  (2) Deliver the walls to the job-site.
  (3) Install the walls on the job-site.

On Gladstone, the architect considered adding 10.2 cm (4”) methane vents to 30.5 cm (12”) stone panels. However, the architect decided not to include them after finding out how much it costs to get the stone fabricator to add them. Regardless, the stone fabricator still drilled slots for anchor bolts and beveled panel edges when necessary (Figure 66).

*Figure 65: Penetration Drilling (Campolonghi 2004)*

*Figure 66: Edge Beveling (Campolonghi 2004)*

### 5.5.8 – Stone Finishes

Stone finishes are important design decisions because they affect stone brightness and color as light reflects differently off of rough versus smooth surfaces. To assist with finish selection, the stone fabricator shipped 4 sample slabs to the curtain wall fabricator to demonstrate the most common finishes: (1) polished (smooth and shiny) (Figure 67), (2) honed (almost as smooth as polished but not as shiny), (3) waterjet (rough), and (4) flamed (similar to waterjet but rougher). The owner and architect visited the curtain wall fabricator's facilities to view the samples but chose instead to finalize their stone finish decision during the Stone Trip.

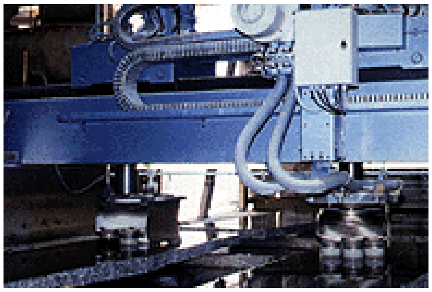

*Figure 67: Automatic Polisher (Elberton 2005)*

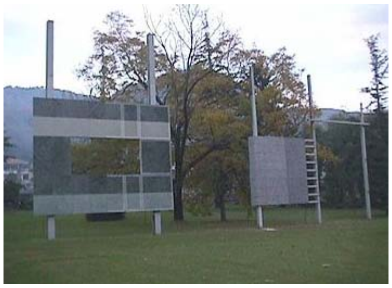

*Figure 68: Mock-Up Area (Campolonghi 2004)*

The stone fabricator prepared a mock-up for Gladstone's Stone Trip to help with the stone finish decision (Figure 68). After viewing the mock-up as well as the stone fabricator’s facilities, the owner and architect decided to use a medium waterjet finish on Gladstone’s curtain walls and a honed finish for panels in the lobby area. Figure 69 illustrates the design process for stone finishes.

### 5.5.9 – Shuffling and Crating Stone Panels

After finishing the panels, the stone fabricator “shuffled” them to ensure similar ones would not get packed adjacent to each other in the shipping crates. This is necessary because curtain wall installers tend to erect panels in the order that they appear in the crates, and for aesthetic reasons (to make the wall in its entirety look more homogenous), architects prefer that similar panels do not get installed side-by-side.

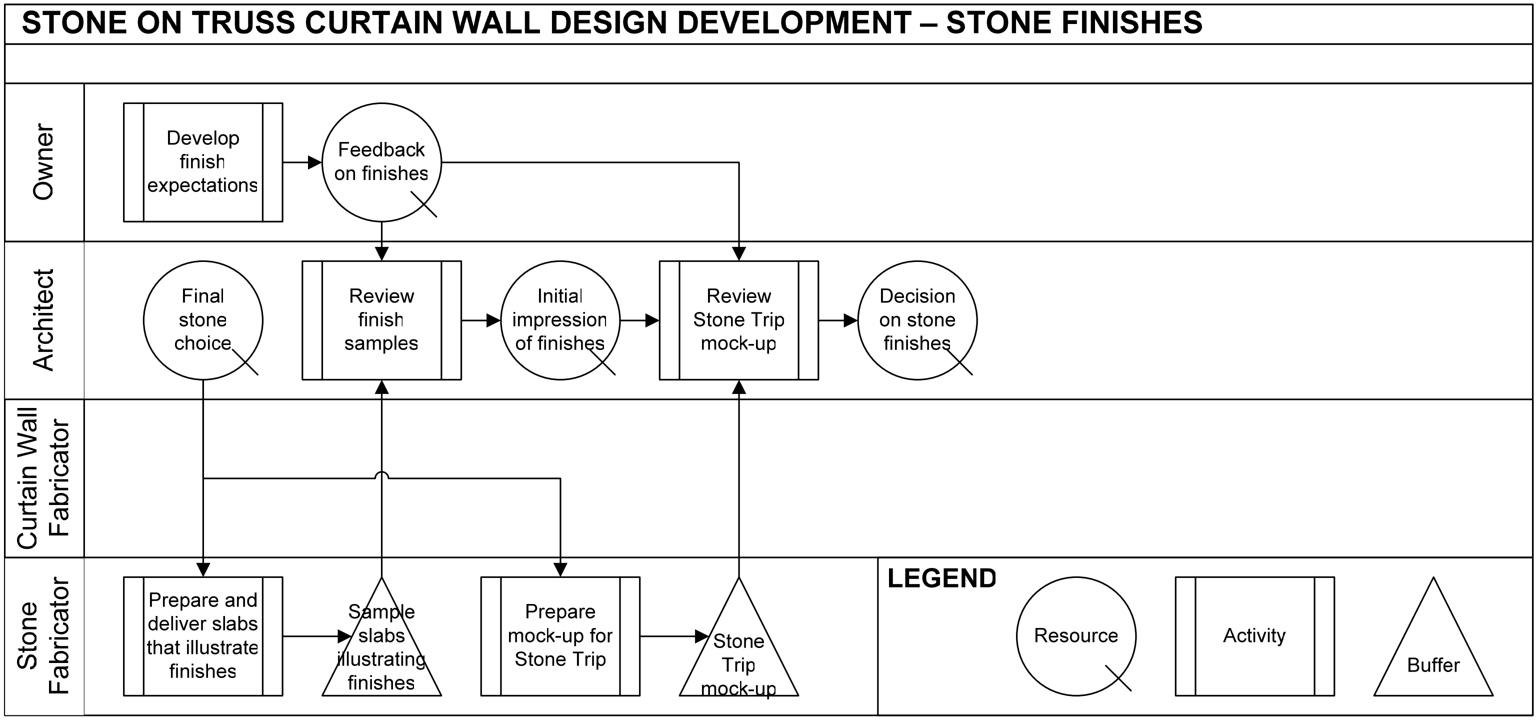

*Figure 69: Design Process for Stone Finishes*

### 5.5.10 – Stone Trip and Stone Production

Often, the Stone Trip settles unresolved issues between the architect and curtain wall fabricator. Touring the stone fabricator's facilities allows the owner and architect to see stone blocks and fabrication equipment in person to help them better understand stone fabrication limitations in terms of space, processes, and quality of product outcomes (Figure 70).

*Figure 70: Stone Fabricator Workshop (Campolonghi 2004)*

Prior to the Stone Trip, many stone design decisions have already been made. Thus, the Stone Trip serves as a milestone for resolving any remaining design decisions. Table 21 lists major stone design decisions and when they were made in relation to the Stone Trip.

*Table 21: Relationship of Major Stone Design Decisions to Stone Trip*

| When decisions were made | Major stone design decisions |
|---|---|
| Before the Stone Trip | • Stone type<br>• Panel thickness and sizes<br>• Location of anchor bolt slots<br>• Location of beveled edges |
| During the Stone Trip | • Allowable range of imperfections<br>• Stone finishes |

The Stone Trip also provides an opportunity for the owner and architect to increase their trust in the stone fabricator's capabilities to supply a major component of Gladstone's $6.6 million building enclosure system.

After the Stone Trip, the stone fabricator had all information necessary to begin production. It took 90 days to complete the following steps to fabricate the stone panels for Gladstone’s stone on truss curtain walls:

(1) Move quarry blocks from stockyard to diamond disks

(2) Cut quarry blocks into smaller blocks with diamond disks

(3) Square smaller blocks with diamond wires to improve gang saw fit

(4) Cut squared blocks to required panel thickness with gang saws

(5) Cut panel sizes with multi-disk cutters while accounting for imperfections

(6) Drill slots for anchor bolts

(7) Bevel edges if necessary

(8) Apply medium waterjet finish

(9) Shuffle and crate panels

### 5.5.11 – Shipping by Stone Fabricator

Based on their ability to fill an entire shipping container, the stone fabricator sent out crates in multiple shipments. They split the Gladstone order into 3 separate shipments and released a shipment every 3 to 4 weeks. Trucks transported the shipping containers from the stone fabricator in Montignoso, Italy, to the port of Livorno, Italy. Cargo ships then transported the shipping containers to the port of Oakland, California near the curtain wall fabricator. Finally, trucks transported the shipping containers to the curtain wall fabricator in Fremont, California.

Using a list of world ports published by the National Imagery and Mapping Agency (NIMA 2001), we calculate the nautical distance between the ports near the stone fabricator and curtain wall fabricator in Table 22.

*Table 22: Nautical Distance between Ports near Stone Fabricator and Curtain Wall Fabricator*

| **Origin** | **Destination** | **Miles** |
|---|---|---:|
| Livorno, Italy | Strait of Gibraltar | 887 |
| Strait of Gibraltar | Panama City, Panama | 4,351 |
| Panama City, Panama | San Francisco, CA | 3,245 |
| San Francisco, CA | Oakland, CA | 3 |
|  | **TOTAL** | **8,486** |

Common diesel powered cargo ships cruise at around 20 knots (23 mph) (Meyer 2005). Thus, the minimum time required to transport stone panels from the stone fabricator to the curtain wall fabricator is 15 days. This does not include time for truck transportation, transfers between trucks and cargo ships, getting through customs, or staging at ports.

## 5.5.12 – Stone Receiving by Curtain Wall Fabricator

The curtain wall fabricator spent 5 days to receive and stage each shipment of stone panels for anchor attachment.

## 5.5.13 – Attaching Anchors to Stone Panels

The curtain wall fabricator inserted 0.64 cm (¼”) stainless steel anchor bolts into the slots (drilled earlier by the stone fabricator) and epoxied them into the stone panels. They used the same size anchor bolt for all panels. The curtain wall fabricator purchased the anchor bolts from a single supplier in San Jose, California. Although the anchor supplier serves other clients, the curtain wall fabricator makes up a significant portion of their business.

### 5.5.14 – Fabricating Trusses and Attaching Angles

After finalizing the truss design and panel sizes, the curtain wall fabricator considered available capacity to decide whether to fabricate the trusses in-house or subcontract the work. On Gladstone, the curtain wall fabricator decided to fabricate the trusses in-house, so they procured materials from a local steel supplier. After combining steel members to form the trusses, they welded stainless steel angles onto the trusses.

### 5.5.15 – Attaching Stone Panels to Trusses

The curtain wall fabricator lifted stone panels into place by inserting the anchor bolts on the stone panels into the angles on the steel trusses. Then, they attached additional bolts and washers to tighten the fit.

### 5.5.16 – Glass Color Family and Coatings

The architect collaborated with the glass fabricator to work out the design for insulating glass units (IGUs), which was developed independently of the glass frame's aluminum extrusion design.

- **Insulating glass unit –** The assembly of "two or more glass plies, separated by a desiccant-filled spacer and sealed with an organic sealant" (Viracon 2004).

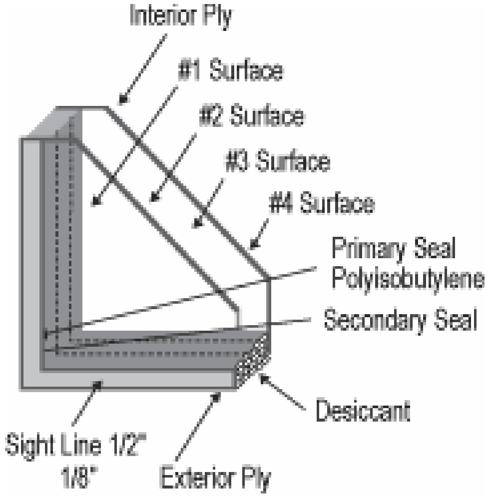

*Figure 71: Insulating Glass Unit (from Viracon 2004)*

Projects often use IGUs, rather than single-pane windows, because they increase the thermal performance of windows.

The glass fabricator's sales force devotes at least 60% of their time to working with architects. When they work with architects, they try to explain how changing glass parameters impacts lead times. The owner also provided feedback during glass design. However, the architect spent the most time working out details with the glass fabricator.

To begin the design process, the glass fabricator sent the architect samples that represent basic glass and coating options for the 6 most popular configurations based on past projects. The glass fabricator tries to keep these samples in stock since they pull materials from the main production floor to use in the sample production line.

The glass fabricator has 7 employees devoted full-time to the sample production line. It duplicates at a miniature level the same work that occurs on the main production line, including handling different permutations of silk-screening, insulating, and coating. The sample production line sends out on average 100 samples daily to architects, glazers, students, homeowners, and contractors.

On the main production floor, the glass fabricator keeps the following 8 types of glass in stock:

- Clear
- Green
- Grey
- Bronze
- Blue/green
- Blue
- PPG Azuria™ – resembles blue Caribbean water.
- Pilkington EverGreen™ – a darker green

The glass fabricator always has clear glass on hand (since it is the most popular choice) and smaller quantities of Azuria™ and EverGreen™ (since they are less popular).

If the architect ordered samples beyond the 6 basic configurations but stayed within the 8 basic glass types listed above, the sample production line handled the request as a custom order. The sample production line can produce custom samples with a maximum lead time of about 8 days (Table 23).

*Table 23: Typical Lead Times for Custom Insulating Glass Unit Samples*

| Coating | Silkscreen | Lamination | Lead Time | Shipping |
|---|---|---|---|---|
| Standard | No | No | 3 days | 2 to 5 days |
| Standard | No | Yes | 6 days | 2 to 5 days |
| Standard | Yes | Yes | 8 days | 2 to 5 days |

Standard glass coatings include:

- **Reflective Coatings** – "Metallic or metallic oxide coatings applied onto or into the glass surface to provide reduction of solar radiant energy, conductive heat energy, and visible light transmission" (Amstock 1997).

- **Low-Emissivity (i.e., "Low-E") Coatings –** "Transparent metallic or metallic oxide coating applied onto or into a glass surface" that maximizes "use of available natural daylight… while reducing summer thermal heat loads and winter thermal losses" (Amstock 1997).

Architects tend to prefer transparent glass over highly reflective glass, i.e., "Ideally, they want a crystal box" (Jackel 2004). However, since Low-E coatings serve as an effective energy barrier for managing heat gain and heat loss, architects are increasingly willing to forego their desire for clear glass and accept the green tint that Low-E coatings add to glass. Thus, aesthetic values are compromised for increasing the building's energy efficiency. The glass fabricator offers 6 standard Low-E coatings, 4 standard reflective coatings, and over 70 custom coatings (Viracon 2004).

If the architect ordered a non-standard glass sample, the glass fabricator would ask a float glass supplier to produce the samples. These non-standard samples usually arrive within a week or ordering. However, if suppliers had the materials on hand, they could ship samples overnight if necessary. The glass fabricator uses 22 different types of float glass for their product line, 8 basic types of which are kept on hand.

After reviewing the first set of samples, the architect settled on a color family. It is common for the glass fabricator to get complaints of "Too heavy" or "Too dark" from architects at this stage of glass design.

### 5.5.17 – Variations of Glass Color Family

With a specific color family in mind, the glass fabricator developed a second set of samples that demonstrated variations of the color family (e.g., lightening or slightly changing the color family) by combining different glass types and coatings.

Architects typically have developed their visual requirements before contacting the glass fabricator. However, if they have not consulted mechanical engineers before working with the glass fabricator, they may not know what they need to choose performance-wise. Cities are increasingly enforcing their own energy codes, and architects need to meet those standards. Architects that know their local energy codes tend to have a better understanding of how their glass needs to perform, but they still benefit from additional input from the glass fabricator. Consequently, at this stage, the glass fabricator might ask architects to clarify their local energy codes so that the second set of samples can begin experimenting with techniques for achieving those standards.

After reviewing the second set of samples and taking into consideration local energy codes, the architect settled on a variation of the color family.

### 5.5.18 – Glass Silkscreen Patterns and Colors

Coatings add weight and can darken the color of glass because they take away visible light. As a result, coatings might make windows look darker from both inside and out. Using the color variation selected by the architect, the glass fabricator developed a third set of samples that introduced silkscreen patterns to test methods for reducing required coatings. The glass fabricator offers 3 standard frit patterns and 12 standard frit colors

(Viracon 2004). Frit color impacts a silkscreen pattern’s “level of reflectivity, boldness or subtleness, and solar performance” (Viracon 2004). Thus, this stage also helped refine the strategy for meeting local energy codes. After reviewing the third set of samples, the architect decided on the balance between using coatings and silkscreens. Figure 72 illustrates the design process for insulating glass units.

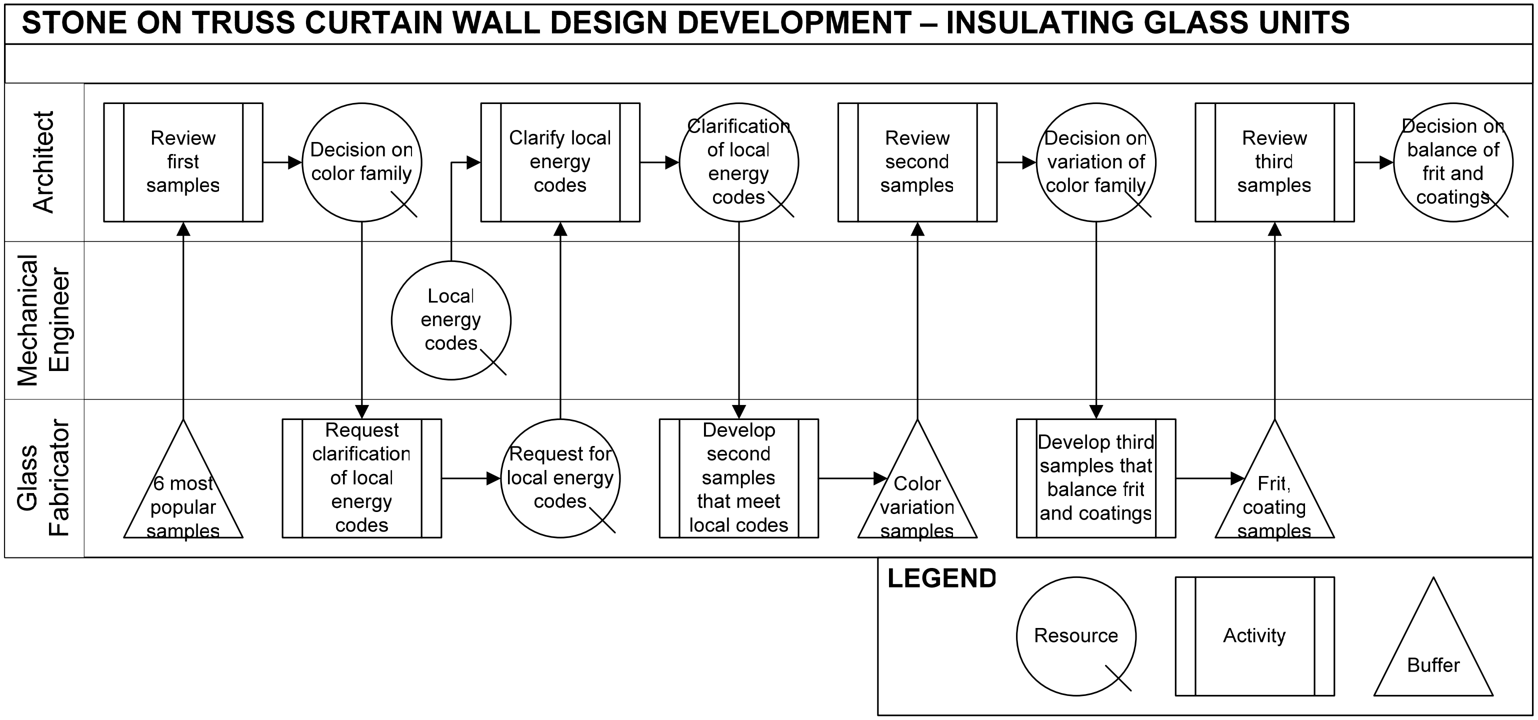

*Figure 72: Design Process for Insulating Glass Units*

### 5.5.19 – Custom Glass Silkscreen Design

The fourth set of samples illustrates different silkscreen patterns. On Gladstone, this step was not necessary since the architect used a standard frit pattern and color.

### 5.5.20 – Design of Insulating Glass Units

The architect and glass fabricator developed 2 types of 2.5 cm (1.0”) insulating glass unit (IGU) designs that used 0.64 cm (0.25”) plies of clear glass spaced 1.3 cm (0.5”) apart. The first design formed insulated frit glass units and the second design formed insulated vision glass units. Glass with Low-E coating applied to the second (#2) surface ( Figure 71) had a nominal visible light transmittance of 70%. Fritted glass applied a standard dot pattern with 40% coverage to the second (#2) surface using a standard color of high-opacity white. Thus, Gladstone’s IGUs used “0.9 acres of glass” to provide “built-in shading as well as much greater insulation than single-paned glass” (Gladstone 2005).

*Table 24: Design of Insulating Glass Units*

| IGU Type | Interior or Exterior Ply? | Heat Strengthened? | Fritted? | Low-E Coating? |
|---|---|---|---|---|
| Insulated frit glass | Exterior ply | Yes | Yes | Yes |
| | Interior ply | Yes | No | No |
| Insulated vision glass | Exterior ply | Yes | No | Yes |
| | Interior ply | No | No | No |

### 5.5.21 – Glass Production Release

Since the glass fabricator handles only custom orders, the following information must be clarified by the architect before production begins:

- Type of glass (i.e., raw materials)
- Conventionally (i.e., use of a glazing channel) or structurally (i.e., use of a silicone sealant without a glazing channel) glazed
- Coating
- Heat strengthening or tempering
- Fritting
- Exact size
- Insulating make-up
- Shipping requirements
  (e.g., how to box and tag glass)
- When project plans to install glass

Furthermore, projects can employ one of the following strategies for releasing parts of a building for glass procurement:

- Releasing according to building faces (e.g., south side of building).
- Releasing according to high volumes first (e.g., larger quantities of glass with the same size). This is in the glazer’s best interest and is easier for the glass fabricator due to fewer required setups.
- Releasing according to floors (e.g., first the 6 bottom floors, then the 24 upper floors). This is popular for buildings in larger metropolitan areas since the lower section of a building may be developed before the upper section.

## 5.5.22 – Glass Materials Procurement

The glass fabricator pulls materials from stock if the order uses one of the 8 standard glass types. If order volume exceeds materials in stock, the glass fabricator orders 152 cm x 305 cm (60” x 120”) glass pieces known as “lites” from suppliers. [NB: “Lites” is also a term for glass panes.] Then, suppliers deliver (1) lites if they have them in stock or (2) glass cut to size for the glass fabricator's customer order if they need to replenish stock anyway. They transport lites on flat-bed trucks with removable A-frames and glass cut-to-size in shipping crates. Procurement can take 1 week for common types (e.g., clear glass) to 6 weeks for specialized types (e.g., glass from Spain).

The glass fabricator considers various factors when managing glass inventories. Subtle but noticeable variations in appearance exist in glass from different suppliers. If an order calls for coated or fritted glass, all materials must come from the same supplier for aesthetic consistency, especially if glass will be used on the outside face of insulating glass units. Glass on the inside face (i.e., the interior ply) is not as noticeable, so the glass fabricator can mix materials from different suppliers if necessary. Furthermore, glass has a shelf-life of 6 to 8 months after which it cannot be coated effectively.

### 5.5.23 – Glass Production

Insulating glass units take 7 to 8 weeks to fabricate. This lead time represents the period from customer order confirmation to order ready for shipment. For orders that require materials procurement, the lead time increases by about 1 week.

Upon material delivery from suppliers, the glass fabricator either (1) rolls A-frames holding lites to the beginning of production, or (2) moves crates of pre-cut glass to an area after cutting. They use a machine with vacuum cups to remove pre-cut glass from crates and place them onto rolling A-frames. This machine is used throughout production.

The glass fabricator has automatic and manual production lines within one building and a second manual production line in a different building. The glass fabricator has 4 cutting lines including the automatic line. After cutting lites, the glass fabricator bar-codes the cut glass and transfers them onto smaller A-frames.

The glass fabricator washes any pieces that require fritting (Viracon 2004). They apply a ceramic frit to one side of the glass using a silkscreen. Then, they use a tempering furnace to heat strengthen both non-fritted and fritted glass. This process also helps the frit bond permanently to the glass. Next, coating equipment magnetically applies a Low-E coating onto both non-fritted and fritted glass. Insulating equipment positions 2 plies of glass 1.3 cm (0.5”) apart and applies sealant around the edges to form a sealed air space.

Gladstone’s glass fabricator is one of the last companies in the US that performs all glass fabrication steps (i.e., cutting, fritting, heat treating, coating, and insulating) under one roof. Only cutting might be performed by suppliers if their production schedules allow it. Newer glass fabricators purchase pre-coated glass to compress lead times. However, silk-screened frit on Low-E coated glass alters in appearance during heat treating. An awkward solution is to place the Low-E coated glass as the #2 surface and then silkscreen the #3 surface of the insulating glass unit ( Figure 71). Thus, Gladstone’s glass fabricator self-performs all glass fabrication steps so that they can continue to apply frit onto the #2 surface, heat treat the glass, and then apply the Low-E coating onto the #2 surface as well.

## 5.5.24 – Shipping by Glass Fabricator

The glass fabricator developed custom shipping crates that can hold up to 907 kg (2,000 lbs) each. An insulating glass unit weighs about 29.3 kg per $m^2$ (6.0 lbs per $ft^2$). Thus, depending on order size, each crate might hold an A-frame that contains up to 5 units. The glass fabricator then trucked the crates to the curtain wall fabricator.

### 5.5.25 – Glass Receiving by Curtain Wall Fabricator

After receiving the shipment of crates from the glass fabricator's trucks, the curtain wall fabricator transferred the crates to the final assembly area of its manufacturing facilities.

### 5.5.26 – Glazing

The curtain wall fabricator combined 15 different aluminum extrusions to form heads, horizontals, sills, major mullions, and vertical mullions for the stone on truss curtain wall. They installed the insulating glass units into the aluminum frames with the help of gaskets and fasteners, among other assembly accessories. Then, they used gray and black sealant to seal exposed joints.

### 5.5.27 – Job-site Installation

In shop assembly, the curtain wall fabricator (1) set stone on trusses and (2) installed insulating glass units into aluminum frames. Then, after one check or several checks with the general contractor, they transported these assemblies directly to the job-site. With the help of a crane, they lifted the stone on trusses into place, followed eventually by the window walls to complete the curtain walls.

### 5.5.28 – Impact of Product-Process Design Integration

Table 25 uses a Work Structuring perspective to illustrate the impact of product-process design integration during stone and glass development on building enclosure system performance. From Table 25, we see that changes in both product and process designs often generated improvements in quality and budget performance.

*Table 25: Product-Process Design Integration during Stone and Glass Development*
*(“Δ” = Changes, “+” = Positive Impact, “–” = Negative Impact)*

| **DECISIONS** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| Location of stone on truss | | Δ | Δ | Δ | + | + | + | + |
| Stone type | Δ | Δ | | Δ | | + | | + |
| Allowable imperfections | | Δ | | Δ | | + | – | + |
| Panel thickness | | Δ | | + | + | | | + |
| Panel sizes | | Δ | | | + | – | + | + |
| Stone penetrations | | Δ | + | | | | + | |
| Stone finishes | | Δ | Δ | Δ | | + | | |
| Panel shuffling | | | Δ | | | + | | |
| Glass color family | Δ | Δ | Δ | | | + | + | + |
| Glass coatings | | Δ | Δ | Δ | | + | | + |
| Frit design | | Δ | Δ | Δ | | + | | + |
| Production release | | | Δ | | | | + | + |
| Materials procurement | Δ | | Δ | | | + | + | |

## 5.6 – Work Structure Mapping

Figure 73 represents curtain wall delivery in the form of a Work Structure map. The stone and glass fabricator produce components that the curtain wall fabricator combines with steel trusses and aluminum frames to form sub-assemblies. Then, the sub-assemblies get delivered to the job-site for installation. Bold boxes represent work that can be done by other project participants or with the use of different equipment. Specifically:

- **Form steel trusses** – can be performed by the curtain wall fabricator or subcontracted out to a steel fabricator.
- **Cut blocks into thin slabs –** can be done with a slower, but cheaper gang saw or with a faster, yet more expensive diamond wire.
- **Cut glass to size** – can be performed by the glass fabricator or a float glass supplier if their production schedule permits.
- **Magnetically apply coatings –** can be performed by the glass fabricator or a float glass supplier that pre-coats glass.

Other activities might be re-assigned or restructured for greater efficiency as well. Thus, Work Structure maps can be used to help identify potential areas for improvement.

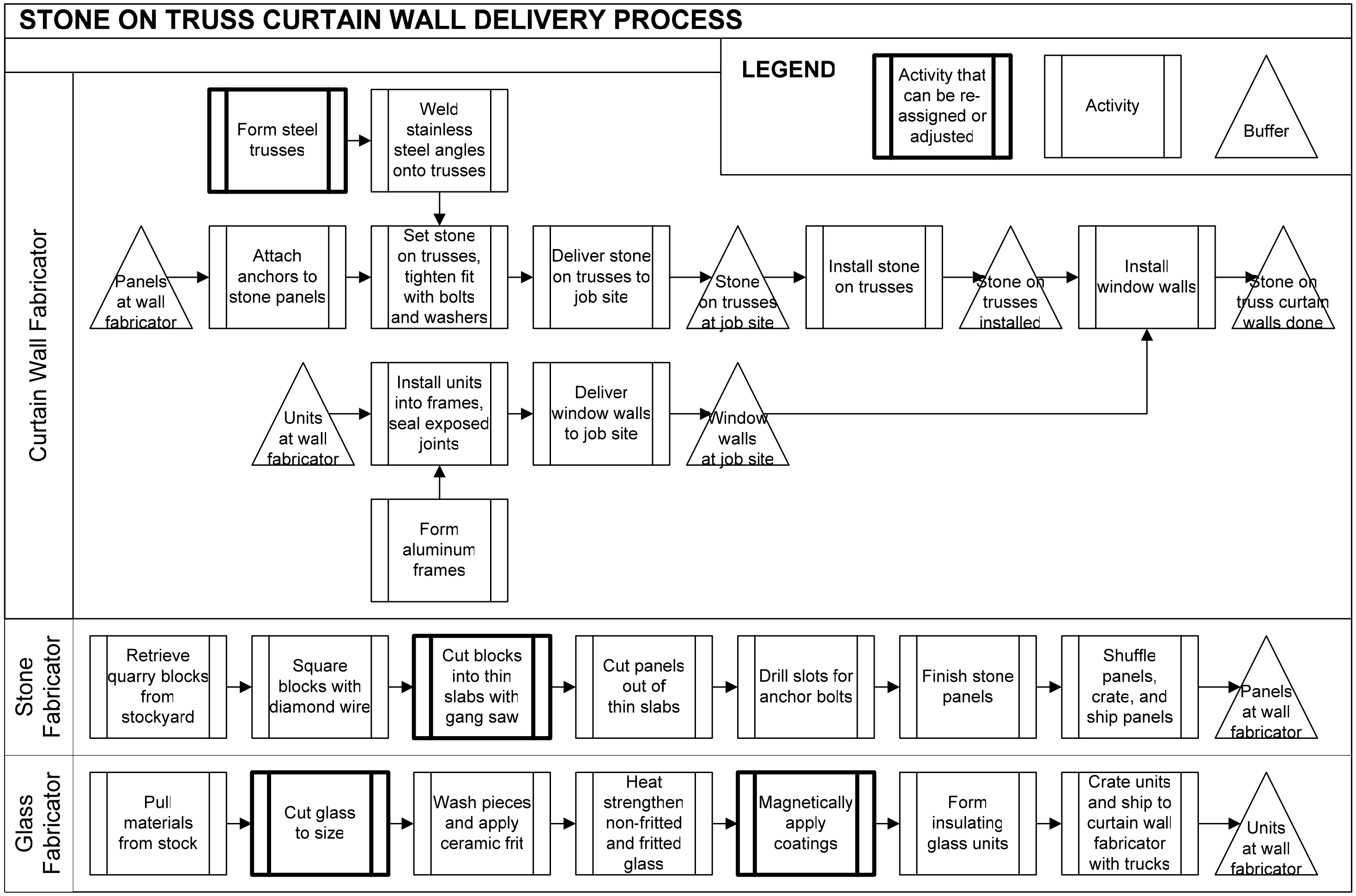

*Figure 73: Work Structure of Stone on Truss Curtain Wall Delivery Process*

## 5.7 – Work Structuring Analysis

### 5.7.1 – Negative Design Iteration vs. Design Decision Incubation

Project participants make design decisions after they feel they have considered a sufficient number of feasible alternatives. If they are not satisfied with readily available alternatives or if it is unclear which alternative is best, they may delay decision-making to provide an opportunity for the discovery or development of better options. Time also allows project participants to reconsider their priorities and gravitate towards a suitable decision. Thus, although it is important to eliminate negative iteration in design, it is likewise important to allow for "design decision incubation."

Table 26 notes the number of times that stone, glass, or visual mock-up design issues were addressed or re-addressed during meetings. This kind of analysis might be used as the first step in understanding when project participants are involved in design decision incubation versus negative iteration in design. When design issues are discussed, project participants can try to assess whether their consideration during the meeting will benefit the project in the long run. Then, they can confirm whether they were correct in their assessment as they proceed with fabrication and installation.

*Table 26: Instances of Design Issues Addressed or Re-Addressed during Meetings*

| **Design Issues** | **Dec 17** | **Jan 14** | **Jan 21** | **Jan 28** | **Feb 12** | **Feb 25** | |
|---|---|---|---|---|---|---|---|
| *Stone Type* | 2 | 3 | 4 | 3 | 4 | 2 | *18* |
| *Panel Sizes, Truss Design* | 6 | 2 | 0 | 2 | 2 | 0 | *12* |
| *Penetration Locations* | 1 | 2 | 2 | 0 | 0 | 0 | *5* |
| *Stone Finishes* | 2 | 3 | 2 | 3 | 1 | 1 | *12* |
| *Glass Color Family* | 1 | 3 | 4 | 7 | 4 | 0 | *19* |
| *Glass Sizes* | 1 | 0 | 0 | 0 | 0 | 1 | *2* |
| *Frit Pattern and Color* | 1 | 4 | 1 | 5 | 2 | 0 | *13* |
| *Glazing Conditions* | 0 | 0 | 0 | 2 | 0 | 1 | *3* |
| *Visual Mock-Up* | 0 | 6 | 5 | 5 | 2 | 0 | *18* |
| | *14* | *23* | *18* | *27* | *15* | *5* | ***102*** |

For example, the owner noted early on that the budget could not accommodate the use of limestone in the curtain wall. However, after adoption of a granite substitute, the architect continued to pursue opportunities for reincorporating limestone, perhaps because they did not believe the owner’s assertion of budget limitations. As a result, 11 of the 18 discussions of stone type dealt with reincorporating limestone into the curtain wall.

However, the owner remained firm in their stance to exclude limestone from the curtain wall. By January 14th, the use of limestone became limited to signage accents. Then, by February 25th (after project participants observed limestone and granite samples during the Stone Trip), the use of limestone was completely eliminated from the project. Before the Stone Trip, the architect must have felt it was worthwhile to work towards an aesthetic goal of introducing limestone. Then, once they finally accepted the owner’s position on limestone, the time and effort spent by the architect on limestone incorporation became negative iteration in design.

Had the owner changed their mind and accepted the architect’s suggestion for limestone inclusion, then the architect’s past efforts to introduce limestone would be regarded instead as design decision incubation. Thus, a fine line exists between negative iteration in design and design decision incubation, and the location of that line depends on the experience level of the owner and the degree to which the owner has finalized their design decisions. Therefore, future research might experiment with techniques for evaluating the degree of owner proficiency to help guide design professionals in their pursuit of design alternatives.

Another example is the development of a 6.7 m x 6.7 m (22’ x 22’) job-site visual mock-up which was required for approval by San Francisco’s Redevelopment Agency (Figure 74). Project participants spent considerable effort to produce the visual mock-up. Unfortunately, since its completion occurred after the Stone Trip, it could not assist with stone design decisions. In addition, by the time it was done, it was also too late to change decisions in window profiles, metal panels, or custom extrusion colors.

If the visual mock-up had been developed earlier, it could have been an instrumental design decision incubation tool for these major curtain wall decisions. Regardless, the visual mock-up still helped with decisions about components with shorter customer lead times such as glass type, frit pattern, standard extrusion colors, and sealant colors. The visual mock-up also demonstrated project progress for Gladstone’s Board of Directors.

*Figure 74: Visual Mock-Up at Job-site*

In contrast, the glass fabricator's process of structured sample review demonstrates a successful approach to design decision incubation. Earlier samples helped architects understand design possibilities and settle on glass type. Later samples helped architects narrow their choices in coatings, heat treatment, and fritting to meet specific project needs. As architects waited for their next set of samples, they had time to reconsider their priorities and earlier decisions. Then, since their design decisions had time to incubate, they were able to finalize glass design decisions when prompted by the glass fabricator.

Thus, future research in Work Structuring should look into developing techniques that reveal when project participants are involved in negative iteration in design versus design decision incubation to help improve the design management process.

## 5.7.2 – Lead Times and the Last Responsible Moment

Clarifying lead times for curtain wall components helps project participants gauge the Last Responsible Moment for making design decisions. Table 27 details approximate lead times for production of stone panels and insulating glass units.

*Table 27: Approximate Lead Times for Stone and Glass Production*

| **Production Activity** | **Stone Panels** | **Insulating Glass Units** |
|---|---|---|
| Sizing and ordering | 12 | 3 |
| Fabrication | 18 | 8 |
| Delivery to curtain wall fabricator | 10 | 1 |
| Shop assembly | 8 | 9 |
| Job-site installation | 13 | 17 |
| *Total (weeks)* | *61* | *38* |
| *Overlapping activities* | *9* | *3* |
| ***Total with overlapping (weeks)*** | ***52*** | ***35*** |

Project participants can clarify these lead time differences as a technique for prioritizing unresolved design decisions. Then, they should focus their efforts on making design decisions for components with longer lead times and postpone decisions for components with shorter lead times. If they make design decisions too early in advance for components with shorter lead times, they increase the likelihood that changing project requirements will require later adjustments to these decisions.

Outlining lead times can also help pinpoint production activities that are good candidates for Work Structuring. For example, restructuring "*who* does *what* and *when*" for stone fabrication or job-site installation of insulating glass units might generate improvements in production efficiency.

Gladstone's Stone Trip seems to be a technique for establishing the Last Responsible Moment for the owner and architect to finalize their stone design decisions. The 5-day trip to Italy requires an investment of time by all attendees and allows about 2 days for viewing the facilities and prepared mock-up. Thus, the owner and architect will likely be ready to complete all stone design decisions by the end of the trip.

### 5.7.3 – Visualization of Work Flow

Figure 75 illustrates the fabrication process for stone panels, Figure 76 illustrates the fabrication process for insulating glass units, and Figure 77 illustrates shop assembly and job-site installation work performed by the curtain wall fabricator.

By analyzing work flow, lead times, and production constraints, project participants can uncover opportunities for restructuring work. For example, stone fabrication lasted 18 weeks (Table 27). The stone fabricator cannot cut panels until after the Stone Trip when the owner and architect decide on stone imperfections and finishes (Figure 75, Table 21). However, they can start retrieving quarry blocks, cutting them into smaller blocks, and squaring them as soon as a stone type is selected.

The stone fabricator can also cut blocks into thin slabs once the curtain wall fabricator settles on panel thicknesses. Getting a jumpstart on cutting thin slabs with the gang saw is a particularly good idea since gang saws may require up to 2.5 days to cut one load (Table 19). Thus, if project participants settled on stone choice and panel thicknesses earlier, the stone fabricator might be able to cut panels immediately after the Stone Trip and help accelerate the overall project. In fact, the curtain wall fabricator mentioned during the January 14th meeting that they had already released some blocks. If the curtain wall fabricator informed the owner and architect about the impact of *when* they make decisions, then they might be more inclined to settle critical design decisions (i.e., those that release production activities) earlier.

Figure 77 combines the structure of fishbone diagrams with the detail of process maps to improve the visualization of subassembly lines that feed into a main assembly line. Project managers can use these maps to identify potential areas for de-coupling work to improve work flow (Tommelein and Beeche 2001). They can also shade in (1) activities when they complete and (2) buffers when they fill. Then, as each group of activities and buffers (e.g., “Prepare stone panels”) completes, project managers can shade in their corresponding sections on the map until the middle assembly line finishes. Thus, maps like these might be used to simply clarify where project managers should focus their efforts by identifying possible production bottlenecks in the form of un-shaded regions located furthest away from the middle line.

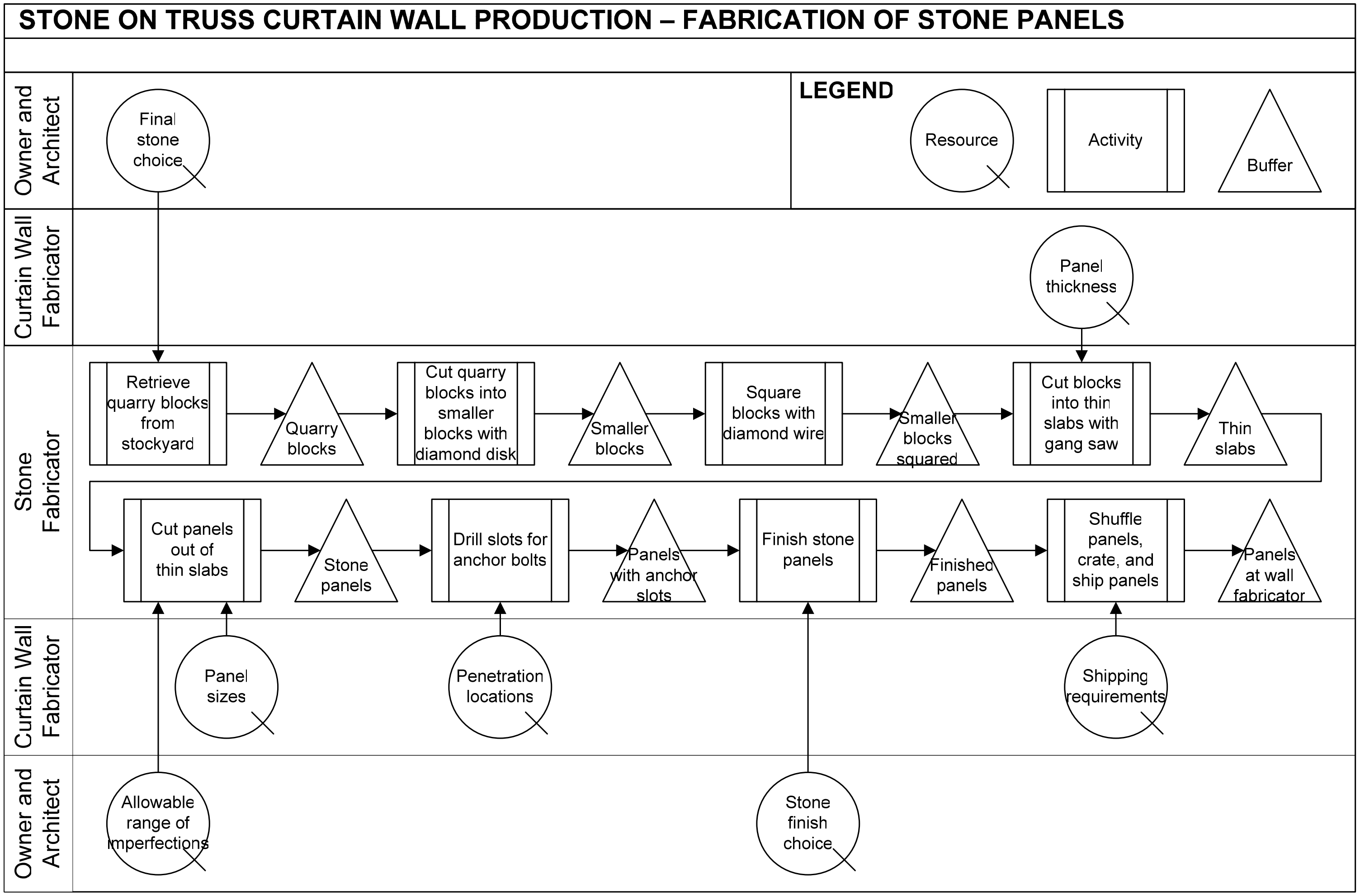

*Figure 75: Fabrication Process for Stone Panels*

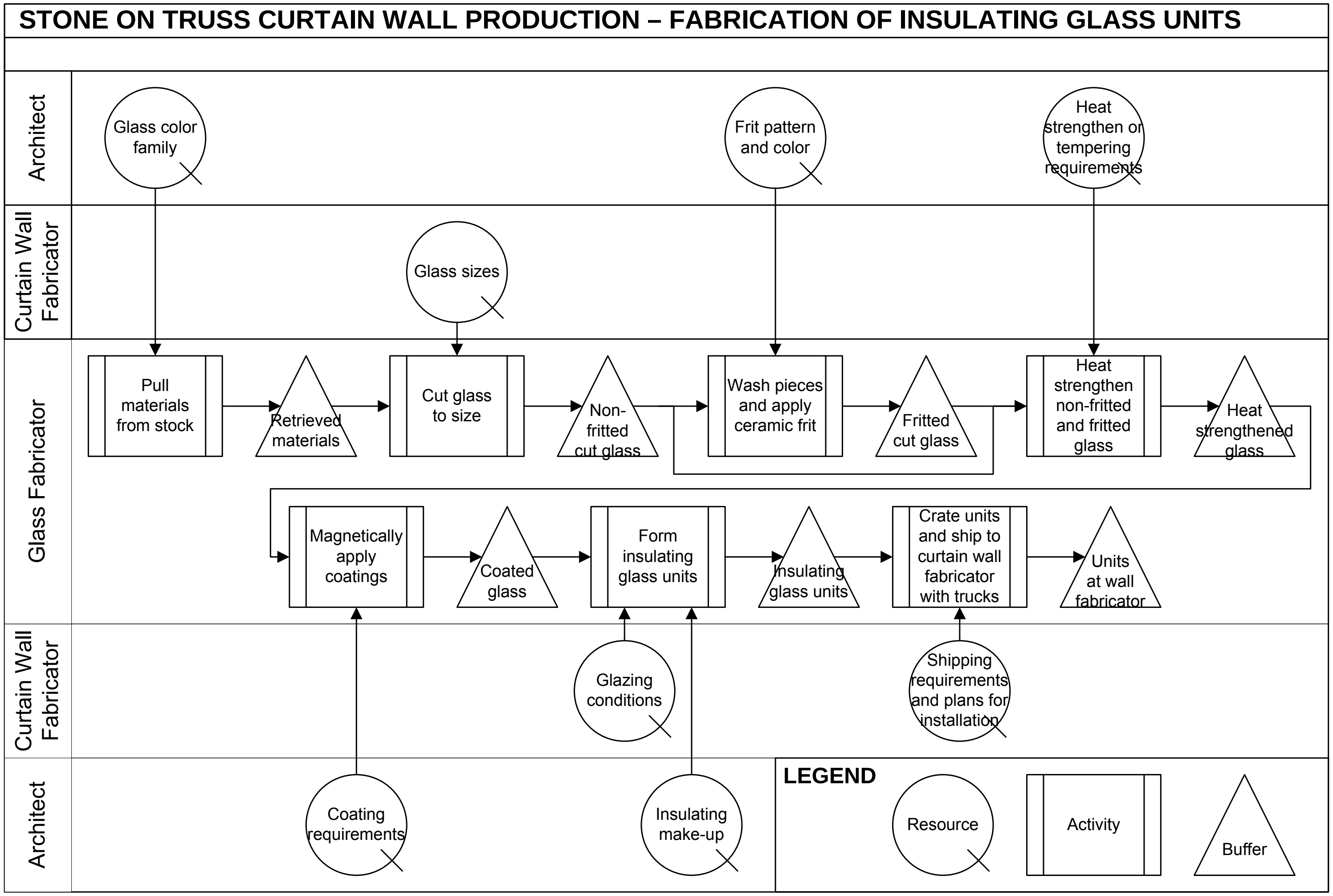

*Figure 76: Fabrication Process for Insulating Glass Units*

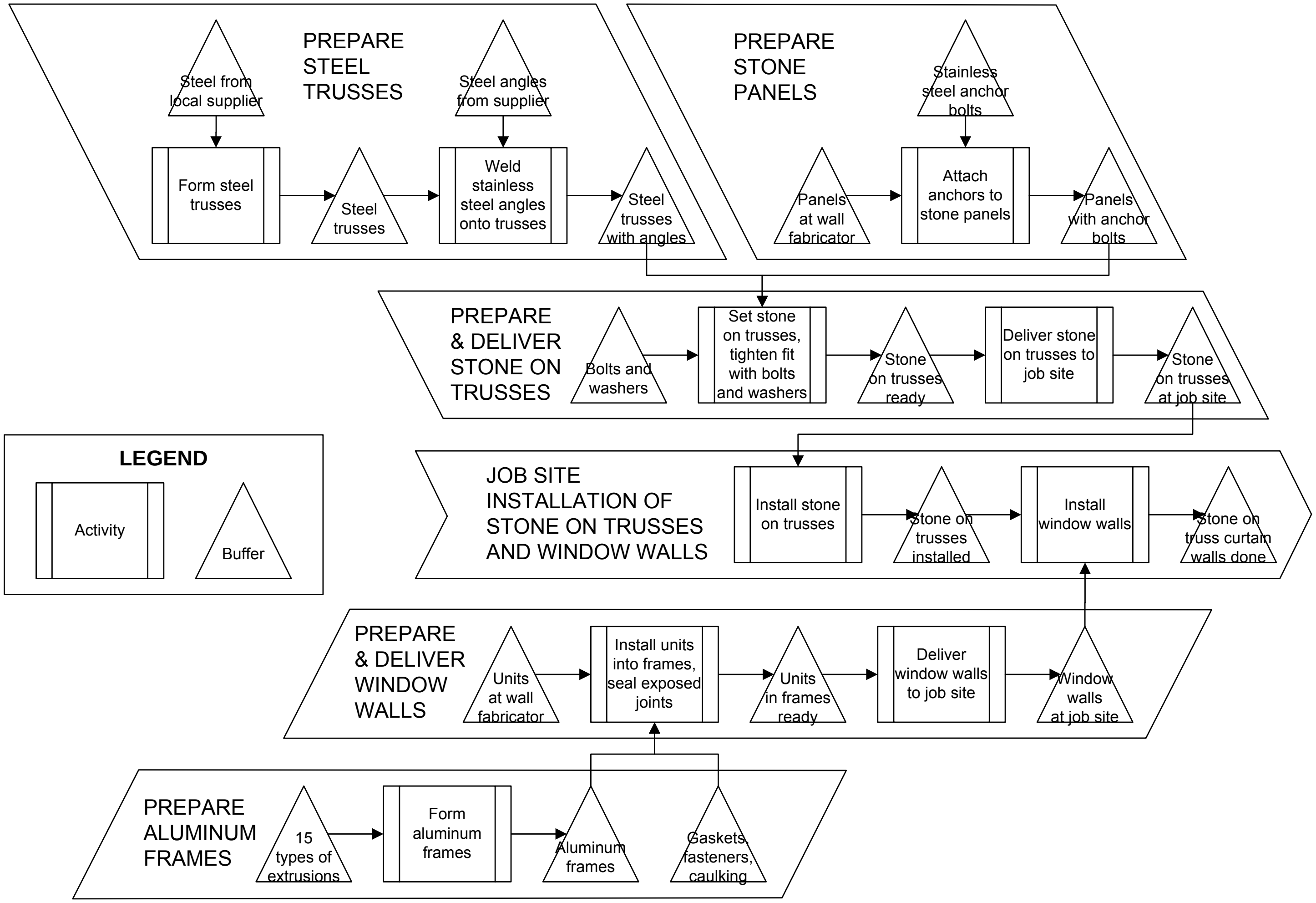

*Figure 77: Shop Assembly and Job-site Installation Work Performed by the Curtain Wall Fabricator*

### 5.7.4 – Creating Work Structuring Transparency

To harness the powers of Work Structuring, one must “see” Work Structuring issues as they emerge, especially during design development. To overcome this barrier, we suggest the use of a table during design coordination meetings to make Work Structuring issues more transparent. The table lists four types of design that are fundamental in the definition of Work Structuring (i.e., supply chain design, product design, process design, and operations design) (Ballard 2000b) and four types of overall project impact (i.e., safety, quality, schedule, and budget). Depending on project needs, planners may choose to use different types of impact (e.g., value, environmental, social, and cultural). Table 28 shows an excerpt from a Work Structuring transparency table. Appendix A contains more detailed tables developed from observations of the first four meetings in Case 3.

For each discussion topic, we generated a tracking number incorporating the date and relative position in the meeting. For example, the first topic addressed during the January 14, 2003 meeting becomes issue “01-14-2003-A” and the next topic becomes issue “01-14-2003-B.” We clarify how each topic changed a facet of design and explain how the change might impact the project. Then, we note “action items” to develop a strategy for resolving Work Structuring issues. When topics reappear later in the meeting or in subsequent meetings, we generate a new tracking number and combine it with older tracking numbers to help us follow the process of topic resolution. This simple format helps project participants view their projects through “Work Structuring glasses” as they consider opportunities for improving project delivery efficiency. Thus, it could be a useful technique for introducing practitioners to the Work Structuring concept.

*Table 28: Making Work Structuring Issues Transparent during Design Coordination Meetings*

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-14-2003-A**<br>12-17-2002-I<br>12-17-2002-D<br>Stone finishes | | Section T1 – water jet. Section ST3 – replace honed granite to match pavement. | | **Action item:** Curtain wall fabricator will inform stone fabricator. | | Provides a more consistent appearance at the base of the building. | | Possible cost impact. |
| **01-14-2003-B**<br>Stone type | | Limestone is only signage accent now. | | **Action item:** Curtain wall fabricator will inform stone fabricator. | | Less limestone results in lower aesthetic quality. | | Reduces cost since limestone is expensive. |
| **01-14-2003-C**<br>12-17-2002-C<br>Glass type | | Architect has not selected glass type. | | **Action item:** Architect will obtain more samples for glass type from glass fabricator. | | Architect prefers less of a green tint in glass. | | |

## 5.8 – Case Study Conclusions

The Stone on Truss Curtain Walls case study examined the production process for stone panels and insulating glass units. Narrowing the scope of study to two components of one curtain wall system within a larger building enclosure system provided an appropriate scale for analyzing the interdependency between design, fabrication, and installation.

Although curtain wall production seemed complicated at first, breaking each step into transformations of inputs into outputs revealed simple explanations for production constraints. Thus, we explored how project participants released production following design completion and raw materials procurement. We also studied how they transferred fabrication responsibilities to other companies when their facilities had limited capacity.

Complexity develops from interdependencies between production steps, but this can be unraveled by tracing work flow. Accordingly, we created process maps to illustrate how design decisions allow (or prevent) certain fabrication steps to begin. We also investigated how project participants managed design handoffs between specialists.

Understanding how value is generated provides insight into production efficiency. Consequently, we examined the impact of product-process design integration on overall project performance. More specifically, we explored the role of the Stone Trip and visual mock-up in curtain wall development.

To advance the Work Structuring framework, we discussed the relationship between negative design iteration and design decision incubation. We clarified how fabrication and installation lead times help gauge the Last Responsible Moment for making design decisions. We experiment with techniques for visualizing work flow by using process maps to highlight the main and sub-assembly lines in production. Finally, we discuss how to familiarize practitioners with the concept of Work Structuring through the use of transparency tables during design coordination meetings.

Pietroforte (1995) noted, “A considerable amount of detail design and engineering is implemented by specialty contractors and fabricators simply because the cutting edge of technology has progressively shifted in their hands.” Indeed, we found this to still be the case in our study. Pietroforte (1997) then noted, “Efficiency of the shop drawing review process would improve… if project-wide liability insurance could be provided by value-conscious owners to all the design professionals involved in a project.”

Gladstone’s collaborative environment existed because the owner was committed to exploring all possible strategies for value generation. Nevertheless, a breakdown still occurred during the 4th meeting we observed when the architect could not maintain the pace of shop drawing review required by the curtain wall fabricator to stay on schedule for aluminum extrusion procurement. The curtain wall fabricator likely communicated in earlier meetings the Last Responsible Moment for completing shop drawing review for aluminum extrusions. However, if project participants do not explicitly note and track such production requirements, they could easily get lost or forgotten.

Project-wide liability insurance might prevent these breakdowns. However, before such practice becomes standard, a Work Structuring perspective can be used in the interim to leverage the Level of Influence of project participants during design development to improve the efficiency of curtain wall fabrication and installation.

## 5.9 – Acknowledgments

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# CHAPTER 6 – CROSS-CASE FINDINGS

We used case studies to examine the concept of Work Structuring because they help us understand phenomena and facilitate theory building (Meredith 1998). We intentionally structured our case studies to focus on different project phases and systems of varying size and complexity to demonstrate the applicability of the Work Structuring concept. Based on the results of our case studies, we develop the following cross-case findings to "help extend the generalizability of the results" (Meredith 1998).

## 6.1 – Similarities across Case Studies

### 6.1.1 – Product design often defines 'means and methods'.

AEC practice maintains that design professionals do not define 'means and methods' because they fall under the scope of contractors. However, our case studies provided evidence to the contrary.

Specifications in Case 1 called for grouted door frames and precast walls. Thus, the process design had already been established as project participants need to install precast walls, install door frames, and grout to comply with these project requirements. Then, improving the process design with alternative Work Structures such as adding a concrete lip or casting frames directly into walls would require modifying the product design.

Specifying the steel indirect fixture fabricator's products in Case 2 allows an electrical contractor to gain numerous process design benefits (e.g., reliable delivery from the fixture fabricator, efficient handling due to storage on pallets, flexible sequencing due to Styrofoam packaging, and faster installation due to mated plugs, pre-lamping, etc.). Likewise, using light fixtures from other companies requires specific installation methods based on the degree to which they have considered and accounted for pre-assembly installation issues when developing their products.

In Case 3, the curtain wall fabricator had established standard product colors and shapes based on common design configurations used on past projects. As a result, non-standard colors and shapes must be managed through customized production processes that typically required additional resources (e.g., materials, skills, and time) to complete. Therefore, the degree of product design customization defined the type of process design required to achieve the specified product design. Furthermore, the owner would lose the ability to develop unique aspects of a curtain wall if decisions for customization were not made by the Last Responsible Moment.

### 6.1.2 – Moving work upstream improves project delivery.

By casting door frames into precast walls in Case 1, project participants can move job-site work to off-site fabrication and generate improvements in both schedule and quality of cell enclosure system delivery.

By modifying the fixture design in Case 2, the steel indirect fixture fabricator moved job-site work to off-site fabrication to streamline installation and moved off-site fabrication work to upstream suppliers to limit work in their own facilities to final assembly. These efforts to move work upstream helped the fabricator drastically improve schedule performance in terms of lighting system delivery.

In Case 3, the stone fabricator had better equipment than the curtain wall fabricator for drilling penetrations and cutting panels to size. As a result, it was important to make decisions on those facets earlier in design development in order to leave sufficient time for the stone fabricator to take care of those steps. Also, the curtain wall fabricator did as much work as they could at their own facilities to minimize the amount of work on the job-site. Due to their efforts, the curtain wall fabricator limited job-site work to the installation of stone-on-truss modules followed by punched window wall units and subsequently managed to install the curtain wall sooner than expected.

### 6.1.3 – Contracts impact feasibility of systems-level thinking.

Contractual agreements establish who pays and who gains in project execution. As a result, if owners wish to benefit from systems-level innovation, they need to provide sufficient incentives for project participants to truly collaborate on Work Structuring.

In Case 1, the use of design-build contracting failed to facilitate integration of product and process design as expected. Instead, contracts established project roles based on product affiliation (e.g., supply or installation of precast walls, grout, and door frames), so project participants optimized the execution of their own work chunk. Local optimization occurred because of habits in thought and action. Therefore, project participants had no incentives to collaborate on developing a more efficient enclosure system for prison cells. Furthermore, since fabricators and specialty contractors held contracts directly with the construction manager, they may not feel they had the liberty to suggest broader, systems-level changes for restructuring work, especially if such changes impacted the nature or amount of work for other companies.

Electrical contractors in Case 2 typically held supply contracts with fixture fabricators. Accordingly, fabricators optimized their role as fixture suppliers and left the task of installation to be handled by electrical contractors. To gain market share, the steel indirect fixture fabricator looked beyond the traditional role of fixture supply to adopt a broader role of lighting system delivery. This systems-level perspective helped the fabricator identify opportunities for adjusting fixture design to streamline the installation process. Then, by generating additional value for electrical contractors, the steel indirect fixture fabricator introduced a competitive alternative for lighting system delivery.

The owner brought the general contractor onto the project early in Case 3 so that the general contractor could provide constructability input to the architect. Then, the curtain wall fabricator joined the project to work closely with the architect in curtain wall design development. The owner’s representative also attended coordination meetings regularly to provide immediate feedback to the architect, general contractor, and curtain wall fabricator during design development. Thus, by supporting a collaborative design environment, the owner fostered a culture of innovation among project participants. The owner’s decision to use natural stone for the curtain wall instead of a less expensive material such as glass fiber reinforced concrete also demonstrated a commitment to aesthetic quality in addition to cost and schedule. As a result, project participants willingly considered the impact of curtain wall design decisions at the systems-level to determine better strategies for generating value for the owner.

### 6.1.4 – A broader view can reveal high-impact changes.

Project participants in Case 1 let traditions of craft and contract dictate Work Structuring. By thinking at a broader level, we reconsidered how the enclosure system for prison cells generated value for the owner and devised different Work Structures for managing integration of product and process design. Our recommendations were well-received by the construction manager – simpler alternative Work Structures were implemented on another project and more involved Work Structures (i.e., ones that required the involvement of additional companies) were considered for future projects. The construction manager even looked into applying such a Work Structure to the installation of hollow metal window frames as well as using it on college dormitory projects. Thus, a systems-oriented view uncovered ideas that could not only alter the project studied, but also revealed opportunities for application in other areas of value generation.

With a systems-oriented view, the steel indirect fixture fabricator in Case 2 identified alternative methods of value generation for lighting system delivery. First, they developed products that could be formed from easier to procure materials. Then, they found ways of moving processing work upstream to suppliers so that work in their own facilities could be limited to final assembly. Finally, they adjusted the design of their products to help streamline downstream work normally performed by the electrical contractor. As a result of these efforts, the steel indirect fixture fabricator developed an alternative lighting system that significantly changed the approach to lighting system delivery. Only then could their products compete on a total installed cost basis against lighting systems provided by other companies.

Project participants met frequently in Case 3 to discuss and understand each other's capabilities and constraints. This regular dialogue allowed them to develop a familiarity with each other and adopt a more systems-oriented view when considering various design options as a group. Then, by working on a common goal of maximizing value for the owner, the group willingly explored a broad range of design options before the owner settled on a specific design direction.

### 6.1.5 – Tolerance management is a Work Structuring objective.

In Case 1, the combination of tolerances from door frames and precast walls introduced the gap that led to grout blowout. If project participants could fabricate precast walls with tighter tolerances, they would be able to minimize the gap and prevent grout blowout. However, this is not possible due to the concrete properties of precast walls and the clearance needed to fit door frames into precast wall openings, so project participants need to identify better ways to manage the combination of tolerances. For example, if door frames were cast directly into precast walls, it would eliminate the need to manage the combination of tolerances between door frames and precast walls. Instead, project participants would need to minimize camber in floors so that door frames are plumb after precast wall installation. Then, doors can open properly. If project participants are able to manage this task reliably, they would be able to deliver a better quality Work Structure within a shorter time frame.

Fixture fabricators in Case 2 initially used extruded aluminum to form indirect fixture profiles because aluminum could be fabricated with tight tolerances to match streamlined profile designs and prevent light leakage. Through new product development, the steel indirect fixture fabricator developed the ability to achieve similar tolerances with rolled steel which was a less expensive and easier to procure material. As a result, due to their efforts in tolerance management, the steel indirect fixture fabricator was able to reliably maintain shorter customer lead times. Then, during the Dot-com boom of the late 1990s, they were able to consistently meet the needs of owners who were willing to accept standard profile shapes and a single shade of white to gain benefits in accelerated delivery of indirect lighting systems.

To simplify the installation process at the job-site, the curtain wall fabricator in Case 3 broke the curtain wall up into unitized pieces based on transportation and lifting constraints. However, depending on the curtain wall design and types of materials used, the joint between unitized pieces may be noticeable from afar. Consequently, project participants who want to eliminate these joints for aesthetic reasons may ask that a stick-built curtain wall system be used instead, even though job-site installation will become extremely labor-intensive. Instead, if the curtain wall fabricator can improve tolerance management for the materials used in unitized curtain walls, they may be able to disguise joints between unitized pieces to improve the aesthetic quality of a unitized curtain wall. Therefore, pre-fabrication and pre-assembly strategies typically require better tolerance management.

### 6.1.6 – Received traditions prevent innovation in Work Structuring.

Companies encourage the preservation of received traditions because they represent techniques that have proven to work on past projects. By using these “tried and true” techniques on current projects, companies hope to generate predictable outcomes which would make their projects easier to manage. However, received traditions may inadvertently encourage companies to accept past inefficient practices as standard ways of doing work.

For example, the construction manager in Case 1 built four earlier prison projects which also specified grouted door frames and precast walls. The construction manager’s continued use of a powerful air-powered grout pump further exacerbated the problem of grout blowout. Since the construction manager was on budget and schedule, this received tradition of grouting door frames was never challenged. Thus, our case study’s revelation of project execution problems on the construction manager’s fifth prison project also showed that the companies involved lacked a culture of continuous improvement.

Companies steeped in received traditions may also have difficulty responding effectively to changing market conditions. For example, aluminum fabricators in Case 2 traditionally took care of all fabrication steps in-house. As a result, the steel indirect fixture fabricator's efforts to outsource some fabrication steps allowed them to not only create a niche market of standardized indirect fixtures, but also dominate this new market as aluminum fabricators strived to introduce competing products.

### 6.1.7 – Successful projects still have room for improvement.

The Daily Reporter, a newspaper that covers Wisconsin construction, awarded the Redgranite project in Case 1 with the "Top Design/Build Project of 2000" (Thompson 2000). It selected Redgranite as an exemplary project because Boldt "finished [the project] on time and within budget" while hiring many local workers in the process.

The San Francisco Business Times awarded the Gladstone project in Case 3 with the "Best New Office R&D Development Award" (Watson 2005). In accepting the award, the Gladstone Institutes recognized how the project participants' efforts to work closely "with Gladstone's operations department and end users throughout the design and construction phases" contributed to the success of the project.

These awards are important because they recognize how projects perform in comparison to industry standards. However, Case 1 revealed how adopting a more systems-level perspective can uncover better methods for structuring work while Case 3 revealed how increasing process transparency can help project participants understand the impact of design decisions on the production system. Thus, despite their achievements in project delivery, successful projects still can have room for improvement.

## 6.2 – Differences across Case Studies

### 6.2.1 – Product supply approach impacts degree of integration.

Each case study involved products with different supply approaches to demonstrate the applicability of the Work Structuring concept (Table 29).

*Table 29: Supply Approaches for Products in Case Studies*

| **Case Study** | **Product** | **Supply Approach** |
|---|---|---|
| Prison cell enclosure system | Precast wall<br>Hollow metal door frame | Fabricated to Order (FTO)<br>Made to Stock (MTS) |
| Architectural lighting system | Steel indirect light fixture | Assembled to Order (ATO) |
| Building envelope system | Stone on truss curtain wall | Engineered to Order (ETO) |

Engineered to order (ETO) products force design professionals to resolve integration between components during design development. In addition, since ETO products will likely be prefabricated within a controlled off-site environment, the finished product can be built with tighter tolerances. As a result, Work Structures that contain ETO products (e.g., the stone on truss curtain wall in Case 3) tend to be better integrated.

In contrast, made to stock (MTS) products allow design professionals to rely on installers to resolve integration between components during job site installation. Consequently, Work Structures that consist of MTS products (e.g., the door frames in Case 1) tend to be more poorly integrated since variation in job-site working conditions will force MTS products to be installed with looser tolerances.

### 6.2.2 – Owner type influences degree of integration.

The owner in Case 1 was a state government organization that worked according to a strict budgetary calendar. As a result, the culture of procurement and equitable bidding practices is particularly strong within this owner organization since money must be allocated fairly and spent within each fiscal year. Therefore, the owner predictably supported a design process that emphasized the procurement of individual components which prevented any possible collaboration between companies that could be misinterpreted as collusion.

In contrast, the owner in Case 3 was a research and development organization whose mission was new medicine development. Consequently, since they had probably seen breakthroughs in medical development resulting from employee collaboration, they likely had a positive attitude towards regular interaction between project participants and encouraged such behavior in the development of their project's curtain wall.

### 6.2.3 – Push for integration can come from any project participant.

In each case study, we found different project participants pushing for improvements in Work Structuring integration. The construction manager in Case 1 initiated our case study and has since become an advocate for improving integration across different project systems through the use of target costing (Ballard and Reiser 2004). Their emphasis on system integration differentiated them from their competitors as they generated additional value for owners. As a result, satisfied owners may reward the construction manager with repeat business on future projects. Similarly, the fixture fabricator in Case 2 improved product and process design integration because it allowed them to generate additional value for electricians who installed their fixtures. Then, with increased popularity among electrical contractors, the fabricator created a new market for lighting system delivery. Finally, the owner in Case 3 pushed for collaboration between project participants so that they would be able to benefit from their collective effort in curtain wall development.

## 6.3 – Conclusions

Based on our cross-case findings, it seems that improving project integration requires drastic changes in AEC practice. In particular:

- Practitioners should acknowledge that product design can often define ‘means and methods’ and use this fact to identify opportunities for improving product and process design integration.
- Moving work upstream requires project participants to develop better strategies for limiting work at the job-site to final assembly of pre-fabricated modules.
- Owners should determine if the contracts they use actually facilitate the value generation they seek from other project participants. They should also determine if they have provided sufficient incentives to project participants to develop innovations in Work Structuring to improve overall project delivery.

Thus, practitioners willing to take such risks will likely establish themselves as leaders in innovative Work Structuring practice.

## 6.4 – References

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# CHAPTER 7 – CONCLUSIONS

## 7.1 – Contributions to Knowledge

To describe and analyze our case studies, we identified and refined a framework for Work Structuring which includes the following components: (1) Language, (2) Structure, (3) "Operators" for analysis, and (4) Applications. Based on this refinement of a Work Structuring framework and the research hypotheses and questions outlined in Chapter 1, this dissertation makes several contributions to knowledge.

### 7.1.1 – Clarification of Conceptual History and Work Structuring Language

To address the research hypothesis, "*Although Work Structuring is an established practice, it is relatively new as a theoretical concept. A theoretical concept is needed to improve practice.*", we explained how the Lean Construction Institute (LCI) in recent years introduced the concept of Work Structuring as a means to study project planning without presupposing contracts, trade regulations, and standard practices such as work breakdown structure (Ballard and Howell 2003).

We used a Work Structuring perspective to describe the challenges encountered on post-World War II projects discussed in ASCE's Journal of the Construction Division to demonstrate how Work Structuring is and has been a fundamental form of planning. We noted related terms (e.g., *work chunks, handoffs,* and *production units*) to articulate a common language for discussion of Work Structuring practice and research. Then, we used Case 1 to confirm how lack of a theoretical framework (i.e., a framework that helps project participants recognize when they are structuring work ineffectively) allows poor Work Structuring practice to propagate from one project to the next.

### 7.1.2 – Visualization of Work Structuring Activity

Our case studies experimented with various methods of visualization to address the research questions, *"How do we recognize when project participants are Work Structuring?"* and *"What methods help to reveal Work Structuring activities?"* By increasing transparency of design, fabrication, and installation processes, each visualization method revealed different aspects of the Work Structuring relationship between supply chain-, product-, process-, and operations designs.

- **Cross-Functional Flowchart / Swim Lane Diagram** – Combined process maps (indicating job-site and off site activities, product flows, and resources/buffers) with contractual relationships to show deployment strategies via handoffs of work. Case studies served as a basis for showing how swim lane diagrams could be used to indicate (1) moments of product customization, (2) work chunks moving upstream, (3) new product development work, or (4) work chunks being re-assigned to other project participants.
- **Ishikawa / Cause and Effect / Fishbone Diagram** – Distilled and re-arranged information from swim lane diagrams (e.g., Figure 77) to help illustrate the subassembly lines feeding into the main assembly line of a production system.

- **Design Integration Table** – Tracked whether changes along different facets of design (e.g., supply chain-, product-, process-, and operations designs) generated positive or negative impacts on the overall project in terms of safety, quality, schedule, or budget. We used these tables to compare examples of Work Structuring in the literature review, alternative fixes for Case 1, fixture features in Case 2, and curtain wall design decisions in Case 3. Such tables can be modified to account for specific areas of owner interest (e.g., sustainability, impact on local markets, and end-user marketability and pricing).
- **Fix-Implementation Table** – Identified project participants responsible for approving fixes, performing fixes, or had work affected by fixes (e.g., Table 6). Consequently, it provided insight into the degree of difficulty for implementing specific fixes and thus a rationale for why some fixes are less likely to be pursued.
- **Supply Chain Map** – Illustrated the various connections between contractual relationships, communication that occurs outside of contractual relationships, site access, and flows of goods. Outlining primary work chunks within supply chain maps (e.g., Figure 51) also assists with the Work Structuring task of reconsidering *who* would be most appropriate to execute specific work chunks.

### 7.1.3 – Identification of Barriers to Better Work Structuring

Addressing the research question, *"What are barriers to the development of better Work Structures?"*, our case studies revealed the following barriers: contractual agreements, trade jurisdictions, received traditions, lack of fabricator agility, difficulty of implementation, and poor production transparency. Future Work Structuring research will likely uncover additional barriers.

In Case 1, we described how contractual agreements, trade jurisdictions, and received traditions of work breakdown encouraged project participants to locally optimize their work. As a result, they had difficulty recognizing and pursuing opportunities for restructuring work to improve product-process design integration.

In Case 2, we discussed how standardization and outsourcing decisions by the steel indirect light fixture fabricator allowed it to create a niche market within the architectural lighting industry. Competing aluminum indirect light fixture fabricators, who had invested heavily in equipment to handle many fabrication steps in-house, lacked the agility to modify their product offerings in a timely fashion.

In Case 3, lack of production transparency prevented project participants from understanding the Last Responsible Moment for making specific design decisions. Although they met regularly to collaborate on curtain wall design, they still missed some windows of opportunity for developing a more customized curtain wall when they did not finalize certain design decisions in a timely manner.

### 7.1.4 – Identification of Work Structuring Steps throughout Project Delivery

The case studies illustrated how Work Structuring happens in different ‘triad’ phases and throughout project delivery (Figure 6). To summarize, first at the start of a project, the owner determines how to pursue owner-specific interests throughout project development. The owner may choose one or a combination of the following approaches: (1) select owner employees to represent owner interests, (2) select a third party (e.g., a construction manager) to act as the owner's representative, (3) hire a design-builder to manage the project, (4) rely on the architect to help identify and represent owner interests, or (5) rely on the general contractor to help identify and represent owner interests. This decision may (or may not) determine which project participants have the greatest influence over Work Structuring decisions.

Second, during Project Definition, the owner decides on project purposes, design criteria, and design concepts with input from selected project participants. These decisions establish the direction of the Work Structuring process as project scope comes into focus. Then, clarification of project scope is a first step towards determining the possible Work Structures that project participants can consider for project delivery.

Third, during Lean Design, the architect interprets the design concepts developed during Project Definition and begins to develop the product design with assistance from other design specialists and fabricators. Product design decisions define the work chunks required for the project, so they help narrow down possible Work Structures. General and specialty contractors involved during Lean Design will also emphasize the consideration of installation issues. Process design decisions define the sequence of work chunks and associated handoffs of work between production units. They may also change the work chunks used on the project if the improved process design fosters better overall project delivery. As the architect finalizes decisions to manage product and process design integration, the project's Work Structure takes shape.

Fourth, during Lean Supply, the architect provides the basic product design to fabricators so that they can develop detailed engineering designs, typically in the form of shop drawings. These shop drawings serve as work instructions for fabrication. During detailed engineering, the Work Structure may be modified if project participants redefine some work chunks and handoffs to better account for fabrication capabilities. The architect allows for such modifications when they approve fabricator shop drawings. Fabrication then transforms the planned Work Structure into individual components or pre-fabricated modules. Then, the fabricator delivers individual components or pre-fabricated modules to the job-site.

Fifth and last, during Lean Assembly, the general contractor and specialty contractors manage receipt of components and modules. Based on the process design which defines handoffs between work chunks, workers begin final assembly of individual components or attachment of pre-fabricated modules. Based on the general contractor's schedule requirements, project participants will decide on the types of production units they will employ to execute planned work chunks. Once components and modules have been installed, the general contractor can then turn the project over to the owner for use and commissioning.

### 7.1.5 – Demonstration of Contractor and Fabricator Impact on Work Structuring

Our case studies supported the research hypothesis, "*Because of their expertise in emerging technologies and direct impact on project performance, involvement of* *downstream players (e.g., specialty contractors and fabricators) in upstream Work Structuring decisions improves product and process design integration."* In Case 1, lack of specialty contractor and fabricator involvement in Work Structuring together with their vested interest in the current process resulted in missed opportunities to improve product and process design integration. In contrast, fabricator involvement in curtain wall development in Case 3 helped project participants make trade-offs between product and process designs. Case 2 illustrated how fabricator innovation in Work Structuring generated a competitive, alternative Work Structure for architectural lighting delivery.

### 7.1.6 – Identification and Development of Principles and Techniques

The Lean Construction Institute's "Business Objectives of Project-Based Producers" chart (Figure 48) provided a comprehensive starting point for identifying Work Structuring principles and techniques. We used it to address the research question, *"Which principles and techniques facilitate better Work Structuring?"* We developed additional Work Structuring techniques (Figure 49) based on insight provided by Case 2 since the new product development effort by the light fixture fabricator demonstrated innovative Work Structuring practice.

### 7.1.7 – Evaluation of the Role of Standardization in Work Structuring

Our case studies approached the research hypothesis, *“Standardization is an effective Work Structuring strategy”* from different perspectives. Case 1 illustrated how project participants had difficulty managing the variability in precasting and installation work due to lack of standardization in door frame sizes. Case 2 demonstrated how standardized product features created simpler fabrication and installation processes. As a result, customers willing to accept standardized fixture features could benefit from faster lighting system delivery. In contrast, Case 3 showed how the stone fabricator introduced variation into the final product by shuffling panels before shipment. Shuffling improves the aesthetic quality of the curtain wall by preventing similar panels from being installed next to each other.

Consequently, while standardization is but one means to reduce bad variability in production (Hopp and Spearman 2001, p. 288), it must be balanced by customization which introduces good variability into production to generate additional value for the owner (e.g., by increasing aesthetic quality which can help improve project acceptance by neighbouring businesses and project marketability to potential tenants). Thus, project participants should quantify the value of standardization and customization in terms of overall project goals to guide decisions in Work Structuring. Then, innovative Work Structuring practice may provide incentives to project participants to investigate the tension between good and bad variability before settling on an appropriate level that maximizes value for the overall project.

### 7.1.8 – Development of a Structured Work Structuring Approach

Addressing the research question, *"What steps should be included in a structured Work Structuring approach?"*, we identified the following Work Structuring steps based on insight from our case studies:

- Identify and prioritize project- and company-related goals to guide Work Structuring decisions. Otherwise, projects will stall when project participants need to resolve conflicting goals.
- Develop guidelines (e.g., based on dollar amount, number of project participants affected, or overall schedule impact) that clarify when it is appropriate for the owner, design team, or project team to resolve Work Structuring decisions.
- Identify or develop alternative Work Structures with feedback from fabricators and specialty contractors.
- Establish potential good and bad variability on a project by deciding on the use of standardized or customized products in alternative Work Structures.
- Select an initial Work Structure which seems most promising in terms of achieving project- and company-specific goals and priorities.
- For the selected Work Structure, identify all directives, prerequisite work, resources, and required for design, fabrication, and installation activities to make handoffs of work between work chunks explicit. If this is difficult to do, then

restructure work to facilitate better handoff definition. Also, clarify criteria for approval of executed work.

- As the project progresses, adjust the Work Structure to accommodate changing project conditions. Thus, the Work Structure evolves organically throughout project delivery.
- Determine the Last Responsible Moment for specific design decisions by clarifying lead times for related product components to increase transparency of the relationship between design decisions and production.

### 7.1.9 – Demonstration of Work Structuring Applicability

As mentioned earlier, we demonstrated the applicability of the Work Structuring concept by analyzing Work Structures containing products that employed different supply approaches (Table 29). We did this by applying a similar Work Structuring approach in identifying work chunks, handoffs, and production units within each case study to analyze how work might be restructured to improve project delivery. Thus, for the research question, *"Should different Work Structuring approaches be used for Work Structures with different Customer Order Decoupling Points (CODPs)?"*, we demonstrated how a common Work Structuring approach could be applied to Work Structures that contain products with different CODPs.

However, different visualization methods might be used based on a project's primary goals. For example, if a project has limited laydown space on-site, then swim lane diagrams might be used to highlight opportunities for pre-fabrication and identify all work that can be moved upstream. If a project wishes to restructure the supply chain to streamline execution of work chunks, then supply chain maps could be used to describe in greater detail work chunks performed by each project participant so that planners can re-evaluate *who* would be best suited to execute specific work chunks.

## 7.2 – Future Research

To our knowledge, this dissertation is the first to have articulated a framework for Work Structuring. The case studies illustrated the applicability of this framework to the delivery of capital projects. They showed the value of Work Structuring when considered in and across different phases of project delivery and when applied to different types of facility components. This first step is significant, but it also reveals the need for follow-on research. Thus, recommendations for future research are provided next.

### 7.2.1 – Further Refinement of a Structured Work Structuring Approach

Future research is needed to test and further refine steps that should be included in a structured Work Structuring approach. Doing so helps address the research question, *“What is the impact of using a structured Work Structuring approach?”* as well as the research hypothesis, *“Adopting a methodical Work Structuring approach facilitates better integration of product and process design.”*

### 7.2.2 – Evaluation of the Role of Teamwork in Work Structuring

Our case studies provided some insight into the research question, "*Should design professionals 'pull' information from fabricators and installers, or is the most effective working structure that of a team?*"

In Case 1, the architect and construction manager nominally formed a team to develop their design-build project. Unfortunately, contractual relationships and received traditions kept their team from 'pulling' information directly from fabricators and installers. As a result, the existence of a team structure in Case 1 did not facilitate an improvement in product and process design integration due to lack of fabrication and installation feedback. Thus, future research should investigate how to develop teams that can really collaborate in Work Structuring.

In Case 2, we did not study the design process for a specific project. However, our interviews revealed how fabricators and distributors can assist design professionals with the lighting design process.

In Case 3, we observed the interaction between project participants working as a team to develop the curtain wall design, and we also saw how the architect often 'pulled' information from other project participants to guide their efforts in design. Based on our case study observations alone, we cannot say for certain the effectiveness of 'pulling' information from builders in comparison to team collaboration by project participants.

Future research could investigate this research question further by studying the differences between projects where:

- Design professionals work on design development and ‘pull’ information from fabricators and installers (e.g., through design-assist contracts)
- Design professionals and installers collaborate as a team in design development (e.g., as a design-build team) and ‘pull’ information from fabricators
- Design professionals, fabricators, and installers collaborate as a team in design development (e.g., via efforts in target costing)

Future research could also reveal how pulling information from fabricators and installers and managing an integrated team approach can co-exist (Ballard and Arbulu 2004). For instance, integrated teams of design and construction professionals that work on the overall project design could pull detailed engineering design (developed in fabrication or installation units) from integrated teams of the relevant engineer and fabricator or installer based on completion dates planned for fabrication or installation.

### 7.2.3 – Study of Projects in which Participants Share Risks and Rewards

Work Structuring deals with *who* should do *what* and *when* in project delivery. Sometimes, removing work from one project participant and adding work to another yields an overall improvement in project delivery. These opportunities for restructuring work are important to uncover and implement whenever possible. However, project participants who discover these opportunities may not share their findings with other project participants because:

- They may be the project participant who should be doing *less* work, so revealing the restructuring idea will reduce their company's work and subsequent profit.
- They may be the project participant who should be doing *more* work, so other project participants may regard them as 'territory stealers'.
- They may not be a part of the restructuring idea at all, so project participants who should be doing *less* work may resent them for not minding their own business.

Projects in which participants share risks and rewards (e.g., projects that use target costing or relational contracting) have incentives for companies to reveal ideas for restructuring work (Ballard and Reiser 2004, Matthews and Howell 2005). Thus, future Work Structuring research could investigate projects in which project participants share risks and rewards to analyze exactly how incentives are aligned so that project participants willingly share with others their ideas for improving project execution.

### 7.2.4 – Translation of Fabrication Capabilities into Work Structuring Feedback

Based on their capabilities and expertise, fabricators may perform some fabrication steps in-house and outsource others. Then, based on trade-offs in cost, schedule, and quality, fabricators will decide to offer standardized or customized products to customers. Knowledge regarding these trade-offs and their impact on fabricator reliability may only surface if design professionals pull such information from fabricators. As a result, design professionals may not explore the full range of realistic alternative Work Structures if they lack understanding of fabrication capabilities.

To address this problem, future research could investigate how to translate fabricator capabilities into Work Structuring feedback. Researchers could also look into how to (1) represent trade-offs between standardized and customized products, (2) clarify the costs and benefits of using pre-fabricated modular units versus assembling individual components at the job-site, (3) plan and design for modularization from the start of the project (CII 2002), and (4) handle increased customer expectations as fabricators strengthen their capabilities in design and fabrication with new tools, equipment, and techniques in process management. Then, project participants can decide *who* would be best-suited to fabricate and assemble individual components, and *where* and *when* final assembly of the individual components should take place.

### 7.2.5 – Documentation of Work Structuring History

If project participants join a project at later stages of development, they may lack the historical perspective and logic behind earlier Work Structuring decisions. As a result, they risk wasting their time on developing ideas that have already been considered. To minimize this waste, future research can investigate how projects can publicly log interaction between project participants to illustrate the Work Structuring history (Fruchter 1999, Udell 2001, Macomber 2002) (Figure 78). Such project logs can provide insight into project evolution so that latecomers can quickly understand what has already been considered and become more effective collaborators in Work Structuring.

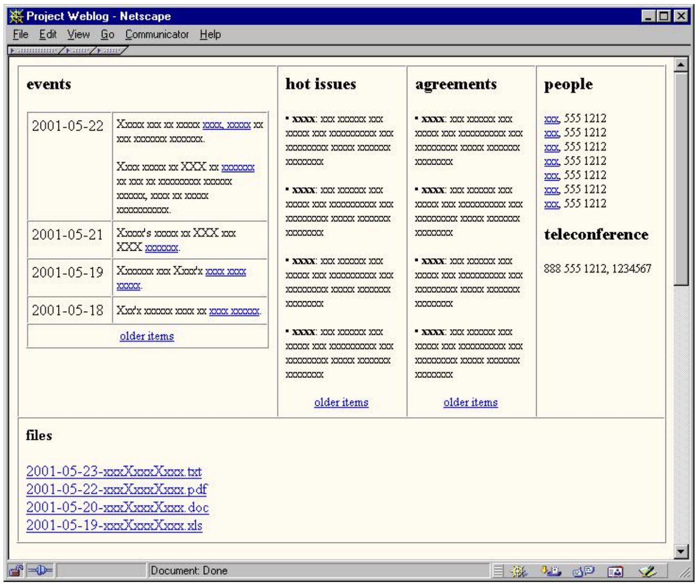

Figure 78: Project Weblog (Udell 2001)

## 7.3 – Closing

Work Structuring is a fundamental form of planning. It determines *what* work must be done on a project, *who* would be best-suited to execute it, and *when* they should be doing it. Through our case studies, we clarified and experimented with the Work Structuring concept. We explained the differences between Work Structuring and other planning techniques, and we highlighted how Work Structuring might be used during different phases of a project. Our case studies provided insight into Work Structuring practice, and we identified methods to overcome the constraints of contracts, trade regulations, and traditional work methods. Finally, we confirmed the usefulness of Work Structuring techniques developed by earlier research and added new techniques to further expand the Work Structuring framework.

The Lean Construction Institute (LCI) has been using the Hollow Metal Door Frames case study in its workshops to introduce practitioners to the concept of Work Structuring.

A typical response to Case 1 was surprise that project participants were not able to come up with more systems-oriented Work Structures. Some practitioners stressed that their company would never be so blind as to not see opportunities for improvement as presented. Others contemplated how their companies might have made similar project execution mistakes in the past. Both types of responses are essential for bringing about awareness and understanding of the concept of Work Structuring in the AEC industry. By opening the discussion of what it means to structure work effectively for overall project delivery, we hope researchers can work together with practitioners to confirm and develop principles and techniques to guide future efforts in Work Structuring.

## 7.4 – References

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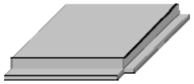
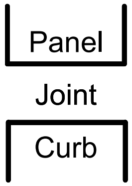
# APPENDIX A

*Table 30: Making Work Structuring Issues Transparent during December 17, 2002 Meeting*

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **12-17-2002-A**<br>Insulation | **Action item:** GC needs to hire insulator. | Architect wants to get insulator involved. | | | | | | GC reworked estimate to include insulation. |
| **12-17-2002-B**<br>Metal panels<br> | **Action item:** Fabricator to determine feasibility of producing 2/16" radius. | **Action item:** Architect to decide on sharpness required of metal panels. | | With new die, Fabricator can produce sharp corners with 3/16" radius on sheets < 82". | | Architect prefers even sharper 2/16" radius. | | $4.40 / SF for dull corners, $7.00 / SF for sharp corners, 12,000 SF of metal panels. |
| **12-17-2002-C**<br>Glass type | Glass choice determines Fabricator's suppliers. | Glass type classified in Fabricator estimate.<br>**Action item:** Architect to confirm glass. | | | | | | Fabricator revised budget estimate. |
| **12-17-2002-D**<br>Stone finishes | | Architect specified water jet and honed finish on granite near base. | | **Action item:** Fabricator to inform Stone Supplier about granite finishes. | | | | |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **12-17-2002-E**<br>Interface btwn wall & sidewalk<br> | | **Action item:** Architect to finalize foundation's curb detail. | GC – "Have stone meet sidewalk or sidewalk meet stone?" | Fabricator needs to plan handset on ground floor. Also, willing to blockout curb. | | Architect wants methane vents camouflaged, flashing against consistent surface. | (Only list schedule impact once it is known.) | |
| **12-17-2002-F**<br>Stone penetrations<br>(Issue changes supplier's operations? List under Operations since supplier's been picked.) | | **Action item:** Architect to confirm 4" methane vents in 12" stone. | | Fabricator cannot add 4" holes to 12" stone without cracks, but quarry can. Fabricator issues stone tickets in Feb. | | | | |
| **12-17-2002-G**<br>Interface btwn wall and roof | | **Action item:** Architect and Structural to determine roof's curb detail (e.g., embed loads, come off steel). | Curb helps waterproofing. GC wants to weatherproof building ASAP. Align & weld pieces before roof pour? | Roof curb introduces access issues for Fabricator. | | | | |

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **12-17-2002-H**<br>Interface btwn wall and electrical | | | | **Action item:** Fabricator to investigate installing light fixtures in panels at plant. | | Architect wants light fixtures installed in panels at plant. | | |
| **12-17-2002-I**<br>12-17-2002-D<br>Stone finishes | | **Action item:** Owner to decide on stone finishes by Jan 6. | | Fabricator needs to issue shop tickets to quarry – sizes (this week) and finishes (later). | | | | |
| **12-17-2002-J**<br>Interface btwn wall and structural | | Fabricator asked how to ID ownership and location of connections. | | **Action item:** Architect provides elevations, Structural and Fabricator to determine connections. | | | | |

*Table 31: Making Work Structuring Issues Transparent during January 14, 2003 Meeting*

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-14-2003-A**<br>12-17-2002-I<br>12-17-2002-D<br>Stone finishes | | Section T1 – water jet. Section ST3 – replace honed granite to match pavement. | | **Action item:** Fabricator informs Stone Supplier. | | Provides consistent appearance at base of building. | | Possible cost impact. |
| **01-14-2003-B**<br>Stone type | | Limestone is only signage accent now. | | **Action item:** Fabricator informs Stone Supplier. | | Less limestone reduces aesthetic quality. | | Reduces cost since limestone is expensive. |
| **01-14-2003-C**<br>12-17-2002-C<br>Glass type | | Section GL3 – standard frit pattern. **Action item:** Architect to select glass tint. | | **Action item:** Fabricator informs Glass Supplier about frit, get samples for glass tint. | | Architect prefers less of a green tint. | | Reduces cost. |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-14-2003-D**<br>Interface between wall and operations | GC would need to hire window washing equipment installer. | If roof accessed > 3x/year, OSHA requires permanent window washing equipment.<br>**Action item:** Architect to confirm if this is necessary. | GC would need to coordinate window washing equipment installation. | | Improves O&M safety. | **Action item:** Owner to resolve associated aesthetic issues with Architect later. | Installation of window washing equipment impacts schedule. | Increases cost. |
| **01-14-2003-E**<br>Metal shades | | Shades simplified. | | **Action item:** Fabricator to inform Metal Supplier. | | | | Reduces cost. |
| **01-14-2003-F**<br>Roofscreen | | **Action item:** Architect and Fabricator to identify cost-cutting measures.<br>Architect to work out roofscreen details. | | | | **Action item:** Owner to decide on design issues (service wall, roofscreen, compressed corners). | | Owner request design revisions to save $250k. |

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-14-2003-G**<br>12-17-2002-F<br>Stone penetrations | | Methane vents removed. | | **Action item:** Fabricator to inform Stone Supplier. | | | | Saves $40k. |
| **01-14-2003-H**<br>01-14-2003-A<br>12-17-2002-I<br>12-17-2002-D<br>Stone finishes | | Only stone finishes can be changed after visual mockup in May. Stone species and extrusions can't be changed. | | **Action item:** If changes for stone finishes, Fabricator must catch slabs in Stone Supplier's production process. | | **Action item:** Owner to decide on any changes in stone finishes. | | |
| **01-14-2003-I**<br>12-17-2002-J<br>Interface between wall and structural | **Action item:** Fabricator to ask Supplier if steel can show up a month early. | | GC can bump up precast if Fabricator can start earlier. Fabricator can start earlier if steel shows up earlier. | | | | GC looking to improve schedule. | |

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-14-2003-J**<br>12-17-2002-B<br>Metal panels | Fabricator found out that sharper corners cost more. | **Action item:** Fabricator to determine price of ground floor outfitted with sharper corners. | | | | | | Sharper corners add $117k to project. Owner to decide if budget can handle additional cost. |
| **01-14-2003-K**<br>12-17-2002-E<br>Interface btwn wall and sidewalk | | **Action item:** Fabricator and Architect to resolve base detail by Tuesday. | Base detail impacts GC's and Fabricator's process designs. | | | | Base detail impacts sequencing and schedule. | |
| **01-14-2003-L**<br>Eyebrow and sunshade | Eyebrow and lunchroom sunshade decision determines required suppliers. | **Action item:** Owner and Architect to decide if eyebrow and lunchroom sunshade use same components by Tuesday. | | | | More variety increases aesthetic quality. | | More variety costs more. |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **01-14-2003-M**<br>Material selection | Change in material requires change in supply chain design. | **Action item:** Fabricator to determine cost impact if spandrels were made of metal. | | | | Owner wants metal spandrels instead of colored glass.<br>Architect notes this change has major aesthetic impact. | | It costs $35k to frit 4 windows. |
| **01-14-2003-N**<br>Mockup: interface between wall and structural | | | Visual mockup will be entirely hand-made by Fabricator. | **Action item:** Fabricator and Structural to figure out how to support visual mockup. | | | | |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **01-14-2003-O**<br>Mockup: intent | | Purpose of mockup determined to be city requirement and changes in color, finishes, and frit pattern. | | | | Mock-up shows 3 vertical conditions (mullions, corners, windows, joints).<br>Owner wants actual stone size of 3'x5'. Metal panels can be smaller. | | |
| **01-14-2003-P**<br>01-14-2003-I<br>12-17-2002-J<br>Interface between wall and structural | | **Action item:** Fabricator to provide connection details to Structural (Mar 15). | GC needs connection information to coordinate with Steel Fabricator. | | | | Ownership of connections affects schedule for Fabricator and Steel Fabricator. | |
| **01-14-2003-Q**<br>Aluminum extrusions | | **Action item:** Owner to decide on extrusion color after viewing mockup. | | **Action item:** Fabricator to inform extruder of color after owner decides. | | | Extruder won't extrude until you settle on color. | |

*Table 32: Making Work Structuring Issues Transparent during January 21, 2003 Meeting*

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-21-2003-A**<br>01-14-2003-C<br>12-17-2002-C<br>Glass type | | One option is off-the-shelf. Division glass can be approved without spandrel glass.<br>**Action item:** Owner and architect finish glass approval by Feb 11. | | Glass decision affects operations design for Glass Supplier. | | | Schedule may be different from old glass.<br>Mixing frit takes 8 to 10 weeks. | Same price as old glass. |
| **01-21-2003-B**<br>01-14-2003-B<br>Stone type | | Fabricator needs direction for limestone.<br>**Action item:** Owner and architect decide on limestone by Italy trip. | | Stone Supplier's operation design depends on color choice. | | Architect wants creamy color. | | |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **01-21-2003-C**<br>Mock-up: metal panels | | Fabricator needs to clarify colors for 4'x4' metal panels in visual mockup.<br>**Action item:** Owner and architect to decide on metal panel colors. | | Metal colors affect Fabricator's operations design because colors are painted on. | | Architect wants to see at least 3 metal colors in sunlight. | | $3 to 4k |
| **01-21-2003-D**<br>Mock-up: caulking | | Fabricator needs to clarify colors for caulking in visual mockup. | | Caulking colors affect Fabricator's operations design. | | Architect not interested in unique caulking colors. 6 standard colors will suffice. | | |
| **01-21-2003-E**<br>Caulking | | **Action item:** Architect clarify caulking joint depth. | | Caulk joint depth affects Fabricator's (Precast) operations design. | | Fabricator (Glass) wants deep recessed caulk joint. | | |

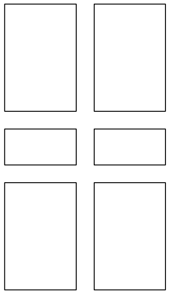
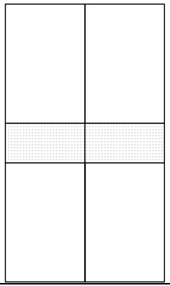
| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **01-21-2003-F**<br>01-21-2003-E<br>Caulking | | **Action item:** Architect confirm use of square backer rods. | | Waterproofing looking into access issues. | | Architect investigating use of square backer rods. | | |
| **01-21-2003-G**<br>01-14-2003-N<br>Mock-up: interface btwn wall and structural | | **Action item:** Structural to assist with support design for mock-up installation. | Reconsider location of visual mockup due to limited impact. | | | | Visual mockup would have been more helpful earlier. | |
| **01-21-2003-H**<br>01-14-2003-O<br>Mock-up: intent | | Owner clarifies visual mockup only allows changes in paint and caulking colors.<br>**Action item:** Owner to decide on colors. | | Changes in color will affect Fabricator's operations designs. | | | Owner should take 1 week to decide on colors after viewing mock-up. | |

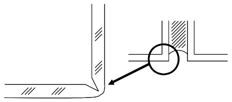
| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **01-21-2003-I**<br>12-17-2002-G<br>Interface btwn wall and roof | **Action item:** GC to determine: Who will take care of concrete curb? GC or Fabricator? | | Concrete curb ownership impacts sequencing, process design. | | | Curb helps with waterproofing. | | |
| **01-21-2003-J**<br>01-21-2003-H<br>01-14-2003-O<br>Mock-up: intent | | Visual mockup intent affects tightness of tolerances. | | Visual mockup tolerances affect Fabricator's operations design. | | **Action item:** Owner and architect clarify visual mockup intent (e.g., visual appearance, workmanship, imitating profiles). | | |
| **01-21-2003-K**<br>01-14-2003-H<br>01-14-2003-A<br>12-17-2002-I<br>12-17-2002-D<br>Stone finishes | | **Action item:** Owner and architect to select light or medium water jet stone finishes on quarry trip. | | Selection of stone finishes affects Stone Supplier's operations design. | | Stone finishes have great impact on aesthetic quality. | | |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-21-2003-L**<br>Moisture control | | **Action item:** Architect to determine location of weep holes. | | Locations of weep holes affect Fabricator's operations design. | | Weep holes contribute to moisture control. | | |
| **01-21-2003-M**<br>01-21-2003-I<br>12-17-2002-G<br>Interface btwn wall and roof | | | Fabricator installs, flashing comes in, fabricator returns to finish up. | | | Flashing impacts stone appearance. | GC suggests extending flashing to avoid impacting Fabricator. | |

*Table 33: Making Work Structuring Issues Transparent during January 28, 2003 Meeting*

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-28-2003-A**<br>Mock-up: glass | | **Action item:** Fabricator bought low-e glass. | | | | | | |
| **01-28-2003-B**<br>01-21-2003-C<br>Mock-up: metal panels | **Action item:** Fabricator instruct paint supplier to buy all 3 colors. | **Action item:** Fabricator will make 3 panels and will demo difference btwn sharp and softer corners. | | | | **Action item:** Owner to pick 2 colors for building. | | |
| **01-28-2003-C**<br>01-21-2003-D<br>Mock-up: caulking | | **Action item:** Fabricator will try different sealant colors and partially recess them. | | | | | | |
| **01-28-2003-D**<br>01-14-2003-Q<br>Aluminum extrusions | Fabricator began die procurement. | Fabricator finished die drawings. | | | | | | |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **01-28-2003-E**<br>Window profiles | | | Fabricator wants to break pieces up with mullions.<br> | | | Architect prefers direct glazing of panes to express structural building.<br> | Fabricator cannot proceed with work until Architect decides. | Definite cost implications. |
| **01-28-2003-F**<br>01-21-2003-F<br>01-21-2003-E<br>Caulking | | | Tape, caulk, peel tape off. | Fabricator notes tooling on caulking is scalloped, not flat. | | Scalloped less effective than flat. | | **Action item:** Fabricator to determine cost for flat caulk joint. |

| **Work Structuring Issue** | **DESIGN** | | | | **IMPACT** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Supply Chain** | **Product** | **Process** | **Operations** | **Safety** | **Quality** | **Schedule** | **Budget** |
| **01-28-2003-G**<br>01-14-2003-J<br>12-17-2002-B<br>Metal panels<br> | | | | Fabricator will back-cut corners of metal panels. | | Cleaner appearance allows for better paint job. | | |
| **01-28-2003-H**<br>01-21-2003-J<br>01-21-2003-H<br>01-14-2003-O<br>Mock-up: intent | | Can adjust finishes, frit pattern and color, metal color. Impossible to adjust stone. | | | | Purpose of mock-up for local agency to approve. | Fabricator to sideline mock-up to focus on aluminum window profiles. | |
| **01-28-2003-I**<br>01-28-2003-D<br>01-14-2003-Q<br>Aluminum extrusions | Before Supplier begins extruding, need to have paint in mass quantity. | | | | | Owner wants to be able to change colors. | Custom color adds 3 months to process (e.g., 3 weeks to procure, 3 weeks to approve) | |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **01-28-2003-J**<br>01-28-2003-H<br>01-21-2003-J<br>01-21-2003-H<br>01-14-2003-O<br>Mock-up: intent | | | | | | Cannot pick custom extrusion color after viewing mock-up and expect to stay on schedule. | Mock-up does not coordinate with production. | |
| **01-28-2003-K**<br>01-28-2003-E<br>Window profiles | Extruder is constraint in supply chain. | | | | | | Lack of resolution delays mock-up. | |
| **01-28-2003-L**<br>01-28-2003-A<br>Mock-up: glass | Fabricator needs to order glass in July. | Owner wants to decide btwn 2 glass choices after viewing. | | | | | Owner suggests installing mock-up week later. | |
| **01-28-2003-M**<br>01-28-2003-B<br>01-21-2003-C<br>Mock-up: metal panels | | Only 2 metal colors to choose from. | | | | | No need to wait for mock-up for colors. | |

| Work Structuring Issue | DESIGN | | | | IMPACT | | | |
|---|---|---|---|---|---|---|---|---|
| | Supply Chain | Product | Process | Operations | Safety | Quality | Schedule | Budget |
| **01-28-2003-N**<br>01-28-2003-I<br>01-28-2003-D<br>01-14-2003-Q<br>Aluminum extrusions | Supplier extruding metal end of June. | | | | | Fabricator concerned local agency will try to change color. | 3 week process to get paint. Have to decide color by end of May. Mock-up viewing at end of May. No float. | |