Work Structuring to Achieve Integrated Product–Process Design

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Abstract: This paper presents "work structuring," a term used to describe the effort of integrating product and process design throughout the project development process. To illustrate current work structuring practice, we describe a case study involving the installation of door frames into walls in a prison. We analyze why various problems existed. To improve the work structuring effort, we apply the "five whys" to develop local and global fixes for the system of precast walls and door frames. The five whys is a technique to elicit alternative ways of structuring work without being constrained by contractual agreements, traditions, or trade boundaries. We discuss the importance of dimensional tolerances in construction and how these affect the handoff of work from one group of workers to the next. We argue that these constraints and tolerance management practices are so embedded that project participants can miss opportunities to better integrate product and process design. We propose shifting the focus of work structuring from maximizing local trade efficiency to improving overall performance in the delivery system of a capital project.

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Work Structuring

Various levels in project organizations determine the structure of work, the way boundaries are established between tasks, the design and location of each task's production process, and the aggregation of the resulting products into completed projects. Designers, fabricators, and contractors each have some input, and work is structured within the traditions and norms of the familiar craft and contractual structures. This current practice typically strives to maximize performance in the preparation of each piece, so project participants often become blinded to important opportunities for improving overall project performance (Paulson 1976).

Work structuring in lean construction is defined as "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 2000). Ballard (1999) initially equated the term "work structuring" to process design and has since broadened the scope of work structuring by equating it with production system design (Ballard et al. 2001). In the remainder of this paper, we advocate this definition for work structuring and illustrate how it differs from current practices of structuring work.

Work structuring answers the following questions (Ballard 1999): (1) In what units will work be assigned to groups of workers? (2) How will work be sequenced? (3) How will work be released from one group of workers to the next? (4) Will consecutive groups of workers execute work in a continuous flow process or will their work be decoupled? (5) Where will decoupling buffers be needed and how should they be sized? (Howell et al. 1993) and (6) When will different units of work be done? In particular, work structuring is a dynamic process that should be re-evaluated in the course of a project. At the project onset, work structuring deals with designing the overall system. As the project progresses, work structuring becomes more focused to guide the design and execution of interacting pieces of impending work. This concept is certainly not new—practitioners have been "structuring work" for as long as construction projects have been in existence. However, we hope to highlight work structuring as a fundamental skill based on organizing principles that should be identified and refined through research.

We use the term work structuring to be distinct from the term "work breakdown structure" (WBS). Contracts, history, and traditional practices of designers, suppliers, and building trades affect how planners conceive of the work required to complete a project. In particular, planners often use a WBS to decompose a project into work packages 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 and Construction Specifications Canada's 5-digit MasterFormat system of classification and num-

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bering (Means 1997). Consequently, designers and builders view 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" (Koskela 2000, p. 49). In this regard, production consists of a sequence of transformations of inputs into outputs, and buffering production involves staging resources before transformations so that the transformations execute as planned. In anticipation of this piece-meal decomposition, designers often leave interface resolution, such as dealing with issues of scope gap and scope overlap, to the builders. They leave tolerance management to installers because they assume that the pieces they have designed will be relatively simple to identify and fit together. By viewing a project as an aggregation of parts, designers may not realize that they can—and, we think, should—design the project as an assembly of *interacting* pieces all the way from design through construction. While the design of each part may appear to be reasonable and logical upon inspection (MCAA 2003), the design of the overall assembly may actually be far from optimal. Not only may it fail to take advantage of overlapping disciplines, the uncertainties and errors created upstream (e.g., during design) may prove to be detrimental to performance downstream (e.g., during installation) (Tommelein et al. 1999).

A piece-meal product-oriented contracting mentality prevents the development of a comprehensive work structure that supports design through construction as well as operations and maintenance. An alternative approach is to use *UNIFORMAT II* (Charette and Marshall 1999) to classify major building components and related site work. *UNIFORMAT II* provides project planners an "elemental framework instead of… a product-based classification" for evaluating alternatives at the early design stage, developing design specifications, and performing cost estimates and analysis. Designers and general contractors could also involve specialty contractors and fabricators early in the design process to take advantage of their insights into process efficiencies (Tommelein and Ballard 1997; Gil et al. 2000). Specialty contractors and fabricators have insight into recent advances in and availability of materials, equipment, and trade skills. Slaughter (1993) noted that innovations on site are needed because problems at the interfaces between products are less likely to be tackled by any one of the product fabricators. This creates a reliance on craft skills, which is difficult today but unrealistic in the future as fewer people are entering the construction trades.

The phrase, work structuring, has been used in manufacturing (e.g., Heizmann 1983). However, that use focused primarily on optimizing productivity on a manufacturing floor, often through automation. The case study described in this paper uses work structuring with a broader meaning tailored to the architecture–engineering–construction (AEC) industry. We also use the term "work structure" to be distinct from the term "work structure process." The Construction Industry Institute (CII) developed the work structure process to distribute roles and responsibilities between the owner and contractor based on key project competencies (Anderson 1997). While it is important to clearly define these roles and responsibilities, other project participants—most notably suppliers—play a significant role in project delivery as well. More recent CII research recognizes the suppliers' and other stakeholders' role and value in project delivery (e.g., Tommelein et al. 2003). In summary, we use the term work structure to generically describe how work on a project will create a product that meets customer needs.

Research Design and Methodology

Case study research is used here to introduce and contribute to the development of a theory of work structuring applicable to the AEC industry. Meredith (1998) notes that researchers use either a rationalist or a case study research paradigm. Rationalist research "employs quantitative methodologies to describe or explain phenomena… [It] is concerned with *explaining* what happens and how." In contrast, case study research "uses both quantitative and qualitative methodologies to help *understand* phenomena. It is more process- or means-oriented and helps the researcher comprehend why certain characteristics or effects occur, or do not occur." Developing such an understanding is the aim of our research.

We decided to focus our case study on a work structure consisting of walls and door frames in prison construction for many reasons. First, the construction manager's Vice President of Production and Process Innovation (formerly a Manager of Project Controls) suggested that this case study be an exercise in operations design to warrant a first run study (Howell and Ballard 1999) as he wanted to improve the productivity of the labor-intensive door frame installation process. However, once it became apparent that problems were rooted in the structure of work as opposed to operations design, the research focus shifted to re-evaluating the AEC project development process. Second, as we try to formalize the concept of work structuring, it makes sense to start with a simple example. The system of walls and frames works well in this regard as it is simple in comparison to other systems that make up AEC projects. Third, door frames in prison walls represent a primary building component within a sizable industry. Between 1990 and 1995, U.S. state and federal officials built 213 new prisons housing more than 280,000 beds to increase their capacity to 976,000 beds (DOJ 1997). What we observed represents accepted and common practice in parts of the United States, so insight into improving the project development process would be of interest to companies employing similar design and construction practice.

For many building projects, the creation of open spaces is a primary activity that brings value to the owner. As the purpose of a prison is to keep inmates confined, the creation of walls and doors brings value to the owner of this project. Consequently, recommendations to improve door frame installation would also be of interest to the owner.

This research began with a site visit to document current practice (Tsao et al. 2000a). We conducted telephone interviews with the construction manager, the precast wall fabricator, the door frame manufacturer, and a grout pump manufacturer to deepen our understanding of the case. We also contacted other materials, equipment, and design service suppliers to help us develop alternative work structures. Then, we visited the site again to develop a cost analysis for the alternatives. During the second site visit, we interviewed the workers, met with the precast wall fabricator, and visited another project that would implement selected recommendations.

Project Background

This case study focuses on the construction of the Redgranite Correctional Institution in the state of Wisconsin. This project consists of four housing buildings that cover a total of 15,310 m^2 (164,800 ft^2) (Thompson 2000). Additional facilities cover another 11,140 m^2 (119,900 ft^2). Housing buildings are two stories tall and their walls are made from precast concrete panels. The first-level floors are slab-on-grade while the second-level floors are precast concrete slabs. In particular, this case study investigates the installation of 285 detention hollow metal door frames into Housing Buildings E and F.

The owner of the project is Wisconsin's Department of Corrections. The Oscar J. Boldt Construction Company is the construction manager. Venture is the project architect. The State awarded Boldt this design/build project based upon a guaranteed maximum price bid of $48 million. The design/build team started work in late 1997 and spent 1998 designing, budgeting, and scheduling the project (Thompson 2000). Construction lasted from February 1999 to November 2000. Before this project, Boldt had already built four prisons in a similar fashion.

The State held a contract with Boldt. Boldt, in turn, held a contract with Venture. Boldt selected Spancrete Industries, Inc. to supply the concrete panels and LaForce to supply the doors and door frames. LaForce is a licensed manufacturer of the Ceco brand doors specified by Venture. While Boldt chose Central City Construction, Inc. to install the concrete panels, they self-performed the installation of the door frames. Boldt hired R. J. Jacques to caulk around the door frames, and then Boldt took care of grouting the door frames.

The project included four primary design packages: Footings and foundation, superstructure, electrical and mechanical, and finishes. Venture released design information about these design packages to Boldt in a piece-meal fashion so that suppliers could begin fabricating pieces early.

The concrete panel supply chain was as follows. First, the State determined its enclosure criteria. With that information, Venture developed an initial wall design with rough openings. Using Venture's initial design, Spancrete developed shop drawings for approximately 3,000 precast concrete pieces and submitted them to Boldt. Venture and Boldt reviewed the shop drawings, approved them, and gave Spancrete permission to proceed. Spancrete fabricated the concrete panels and then delivered them to the job site. The lead time from Boldt's receipt of Spancrete shop drawings to site delivery of the panels was about 12 weeks. Venture specified most panel sizes although they did not have all details on the mechanical requirements (e.g., louvers, air intake and exhaust ducts) for panel penetration. When early design data changed later, several mechanical openings had to be cut on the job site. This was an expensive labor-intensive process that Boldt tried to eliminate in subsequent projects.

The door frame supply chain was as follows. With the State's enclosure criteria, Venture developed the door bid package containing door and door frame designs within a door schedule. Venture developed the door bid package 5 months after Spancrete developed the precast wall shop drawings. LaForce submitted a bid to supply the frames. Boldt approved LaForce's bid and gave them permission to proceed with fabrication. From Boldt's receipt of LaForce shop drawings to site delivery, door frames took about 6 weeks, and door hardware took about 10 to 12 weeks.

Central City installed the walls and Boldt installed the door frames. Then, following Venture's caulking specifications, Jacques caulked the door frames. Boldt subsequently installed a plywood fix (which will be discussed later) and pumped grout into the door frames. Finally, once the grout had set and Boldt removed the plywood fix, Jacques returned to fix any damaged caulking. Tsao et al. (2000a) illustrate this door frame and concrete panel supply chain.

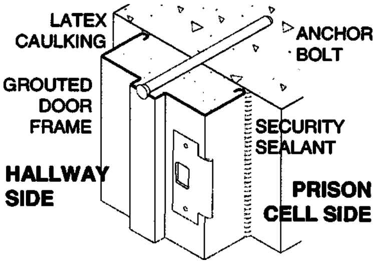

Fig. 1. Grouted door frame against precast concrete wall

Door Frame Installation: Current Practice

Hollow Metal Door Frames

Door Frame Installation

Boldt installed the hollow metal door frames according to prison plans. Fig. 1 illustrates the door frame detail in three dimensions. Boldt's installation procedure is the following. First, the installer moves a frame into the cell. He then uses a level to draw a plumb line to mark where the frame should be installed. Next, he positions the frame into the door space and places the frame against the plumb line. Then, he aligns the frame by using a level and wooden shims. Finally, he installs anchor bolts through the frame and into the precast wall, turns them as tightly as possible, grinds the heads of the bolts down, and applies a Bondo filler over the ground bolt heads.

Caulking Procedure

Once a frame is installed, the next step is to caulk the seam that separates it from the precast concrete panel. Jacques' procedure is the following. First, a worker cuts the shims off with a hand chisel, a procedure called "trim out," so the shim will not protrude through the caulking surface. Then, he inspects the gap between the frame and the wall to see if the caulking will stay in place. If the gap is too wide, the worker inserts a foam backer rod to bridge the gap and caulks directly over it. Usually, the worker first caulks along the door jambs and then caulks along the header. Finally, he brushes the caulking to finish the job, a procedure called "feathering."

Detention Door Frames

Caulking and Grouting Procedure

In prison construction, the door frame installation process differs from standard door frame installation processes due to added security measures. At Redgranite, Venture specified that frames be grouted. In addition, Venture required that security sealant be used along the cell side and hallway side edges of the door frames. In response to a request by Boldt, Venture changed their caulking requirement by allowing latex caulking to be used on the hallway side of the frames. Latex caulking is the type used in bathrooms and kitchens. It is not used inside cells because inmates may attempt to remove or eat it. Latex caulking contains ethylene glycol and eating large amounts of it can result in serious illness or even death. Security sealant is about 55 MPa (8,000 psi) in strength, so it effectively resists inmate tampering. We believe the purpose of caulking or sealant is to (1) prevent grout from leaking out during installation and (2) prevent inmates from having access to any gaps that might develop between the grout and the wall.

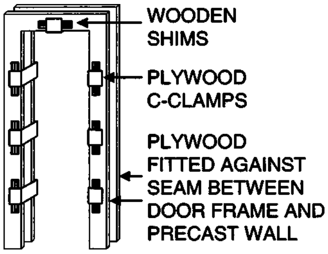

Fig. 2. Plywood fix shown without wall

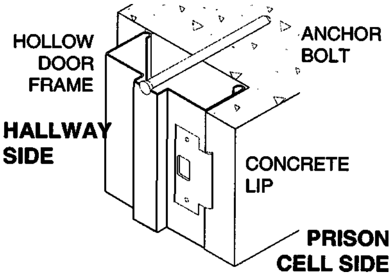

Fig. 3. Concrete lip fix

Venture specified a grout with a strength of at least 14 MPa (2,000 psi) and left it up to Boldt to develop the mix. Boldt was also responsible for grouting the frames. The crew used an air-pressure powered grout pump operating at 30 MPa (4,350 psi) for this application. When the crew developed an initial mix, they found that it did not pump well into the frame due to too much coarse sand. After consulting two other contractors who had performed similar work, they tried four other mixes until they found a good ratio of sand, cement, and water. Boldt decided that the final mix was adequate, informed Venture of their mix design, and used it on Redgranite.

Boldt pumped grout through two holes in the frame called "grout ports," located 76 mm (3″) below the header, one on each doorjamb. A grouting crew first fills the doorjambs halfway. Once this grout has set, the crew then fills the remaining halves and the header. Unfortunately, this procedure had problems. During placement, grout leaked through the cracks between the frame and the wall, blowing out the foam backer rods and caulking.

As frames were already installed when they began grouting, any leak prevention system had to be applied to the outside of the frame. At first, Boldt tried to use the latex caulking and security sealant as a barrier, however both the caulking and sealant kept blowing out. To prevent further blowout, Boldt devised a "plywood fix" (according to Boldt, other contractors use similar fixes). They cut two large U-shaped pieces of plywood sized to fit directly against the seam between the door frame and precast wall (Fig. 2). They built C-clamps out of plywood and used them to hold the two U-shaped pieces together against the door frame. Workers added wooden shims between the C-clamps and the U-shaped pieces to tighten the fit. After pumping the grout and allowing it to set, they removed the plywood fix. Sometimes, the plywood's removal damaged the caulking, so Jacques had to recaulk the frames. However, after developing experience in applying the plywood fix, workers managed to remove it without damaging the caulking, so Jacques did not have to recaulk every frame.

The plywood fix was unwieldy and time consuming. It took about 10 min to install and about 10 min to remove and relocate. For this reason, Boldt had selected the grouting process with the plywood fix as a candidate for a first run study. A first run study accepts the existing design and develops solutions that can work within the current contractual relationships. However, when we applied the "five whys" to unravel aspects of the plywood fix, it became apparent that problems were more deeply rooted in the structure of work. This case study is a means to understand what happened and to determine systematic means to eliminate the need for "plywood fixes" on future projects.

Application of the Five Whys

The five whys is a quality management technique of problem solving that tries to find the root cause of a problem. Once a problem occurs, workers should ask and answer why it occurred at least five times in succession until they identify an actionable root cause. The strategy for fixing the system is to eliminate the root cause to avoid repeat occurrence (Wilson et al. 1993). The "five whys" is an integral part of the Toyota Production System (Ohno 1988, p. 17) that became known as "lean production" in the United States. It is a useful technique in the lean construction tool set as well. The following paragraphs begin with a discussion of a "why?" followed by details regarding local and global fixes that address the "why?"

1. **Why did caulking and foam backer rods blow out?** Caulking and backer rods blew out because of the hydrostatic pressure developed by wet grout during the grouting process.

Security Sealant Fix. This fix applies security sealant on both the inside and outside edges of the frames to prevent grout blowout. It implements Venture's original caulking specifications. The objective of the fix is to prevent blowout when the workers grout the door frames.

2. **Why did grout leak through the cracks?** Grout leaked through the cracks due to the high pump pressure and thin grout mixture. With those two factors, the cracks were not tight enough to hold back the grout. This lack of tightness is the reason why workers introduced backer rods to provide support when caulking over wide cracks. Since backer rods and caulking combined could not hold back the grout, the grouting crew introduced the plywood fix.

On-Site Weather Stripping Fix. Boldt could try to tighten the seal between the frame and the wall. Some kind of weather stripping material might be glued to run along the perimeter of the frame prior to installation to replace the backer rods. Tightening the anchor bolts would compress the weather stripping, thereby providing a tight seal. However, security sealant would still have to be applied to the prison cell side of the frame to prevent tampering.

3. **Why was grouting of the hollow metal door frame needed?** We do not know the origin of the grouting requirement but speculate that grout adds to security by (1) protecting anchor bolts, (2) providing a bond between frames and walls while making the frame heavier should an inmate try to push the frame out, (3) filling the hollow frame and thereby preventing inmates from hiding objects in it, and (4) making it more difficult to disable any electrical lock mechanisms.

Concrete Lip Fix. One way to eliminate the need to grout is to prefabricate walls with a concrete lip that protrudes on the prison cell side of the frame (Fig. 3). Then, inmates would see only a recessed door and concrete wall since the lip blocks access to the frame completely. Once the frame is anchored against the lip, workers could apply latex caulking or weather stripping on the hallway side of the frame. The gap between the concrete lip and the frame might also be bridged with security sealant to prevent inmates from storing contraband in the seam.

When asked if this fix was feasible, Spancrete noted that introducing a 51 mm (2 in.) lip is relatively simple and it would not add much cost to the precast concrete walls. Fabricating such a lip requires adding a block to the wooden forms, increasing the amount of concrete and meshing used, and shifting a piece of reinforcing bar to strengthen the lip. Spancrete would also have to keep the lip from being damaged during transport and installation. In addition, Boldt should confirm if Venture and the owner are willing to let the frames remain hollow in this situation.

Heavy Gauge Steel Door Frame Fix. Another method to eliminate the need for grouting is to replace the 14- and 16-gauge hollow metal door frames with heavier 10- or 12-gauge frames. Using a heavier gauge steel might make the frame too heavy for an inmate to deform or push out. However, this fix requires that security sealant is strong enough to prevent inmates from tampering with anchor bolts, hiding objects in frames, disabling electrical locks, etc.

4. **Why Were There Cracks Between the Door Frames and Precast Panels?** First, door frame installers need to have a 3 mm (1/8 in.) or so opening between the frame and the wall to slide the frame into the panel opening and plumb it. Second, this opening will vary in size along the frame as a result of dimensional tolerances (stochastic variation relative to the design dimensions of a product) during fabrication and placement of the concrete walls and metal frames. Cracks are to be expected when surfaces touch each other in any assembly of parts because it may be difficult to manufacture each part with a smooth surface. Smoothness is a relative concept and achieving it comes at a cost. In addition, materials change in dimensions over time (e.g., shrinkage cracks, deflection and settlement cracks, and cracks resulting from wear). They may also expand or shrink with temperature changes throughout the day. The construction industry has developed many kinds of materials and techniques to fill cracks, to cover them up, to make them water or air tight, to provide structural integrity to the assembly, or to meet other functional requirements.

Tolerance Fix. Tolerances are specified by contract. They represent acceptable variation. Nevertheless, if not specified and 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 a detrimental impact on those downstream in the supply chain.

On this project, Venture developed design drawings that showed rough openings in the walls. Using those rough openings, Spancrete developed precast wall shop drawings. The recommended tolerance for openings in precast walls is 6 mm (1/4 in.) (Freedman 1996, p. 162). (Note that product tolerances mentioned are assumed to refer to one standard deviation removed from the mean specified dimensions. Also note that all unit conversions in the figure and text are approximate.) As Spancrete builds walls within a tolerance of 3 mm (1/8 in.) and due to field requirements of providing a 3 mm (1/8 in.) gap for installers, Spancrete's rule of thumb is to increase the dimensions given by the architect by 6 mm (1/4 in.) on each side of the door opening. Spancrete thus plans for openings that are 6 mm (1/4 in.) taller and 12 mm (1/2 in.) wider than Venture's specified design. Spancrete's shop drawings reflect these modifications.

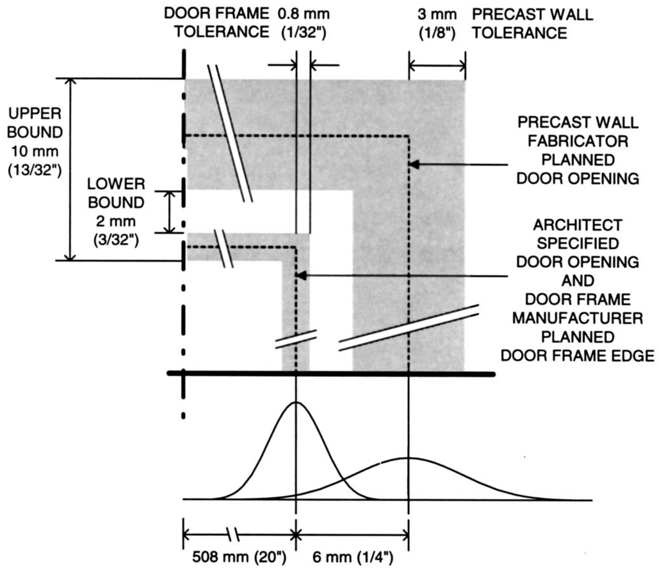

Fig. 4. Tolerances on door frame and precast concrete wall

A few months after Spancrete's shop drawings had been approved by Boldt and Venture, and fabrication of precast walls had started, Venture developed a bid package that specified the frames within a door schedule. LaForce submitted a bid to supply the frames using the door bid package and the door openings shown in Venture's initial design drawings. LaForce built frames within a tolerance of 0.8 mm (1/32 in.) (Fig. 4). A door specified as 914 mm (3 ft) wide to be used in a door frame that is 51 mm (2 in.) thick on each side is built with a matching frame width of 1,016 mm (3 ft 4 in.). Spancrete's corresponding opening would then be 1,028 mm (3 ft $4\frac{1}{2}$ in.) wide, leaving a horizontal gap of 12 mm (1/2 in.).

Poor quality in fabrication and installation results in frames not fitting in the panel opening. When frames and panels did not match, swapping frames out sometimes resulted in a fit. Alternatively, when openings were too small, workers ground the concrete. When openings were too large, workers bridged the gap with masonry infill. Workers then installed the plywood fix to avoid dealing with random blowouts later.

The computed range in dimensions for the opening between the wall and the frame are:

- Lower bound $=(\text{mean value}_{\text{panel}}-\text{tolerance}_{\text{panel}})-(\text{mean value}_{\text{frame}}+\text{tolerance}_{\text{frame}})=2$ mm (3/32 in.), and
- Upper bound $=(\text{mean value}_{\text{panel}}+\text{tolerance}_{\text{panel}})-(\text{mean value}_{\text{frame}}-\text{tolerance}_{\text{frame}})=10$ mm (13/32 in.).

These numbers assume that the frame is perfectly centered in the door opening (Fig. 4). If not, the lower bound may be 0 and the upper bound up to 20 mm (13/16 in.). Note also that the tolerance range may be exceeded on occasion, which is why Fig. 4 shows bell curves (normal distributions) to depict the range of variation.

5. **Why are Door Frames and Panels Fabricated Separately?** These two parts are fabricated separately because they require different materials, knowledge, skills, and fabrication tools. Company specialization has further led to this division of labor. Through such fragmentation, the AEC industry loses valuable opportunities for integration.

Precast Fix. Why not cast the frame directly into the walls (i.e., use the frame as part of the formwork)? When Boldt asked

Spancrete if they could implement this fix, Spancrete was confident that they could. In fact, Spancrete mentioned that the cost to implement this fix is negligible because the time they normally spent blocking out the door openings would be spent instead on positioning the door frames into their wall forms. The feasibility of this fix depends on field quality issues since a primary concern is making sure walls and therefore doors are plumb so that they open properly. In addition, Spancrete needs to work out how to make this fix work on levels with precast, prestressed hollow core floor slabs that are thin and would not allow the same wall installation flexibility as levels with a slab on grade. Spancrete is also 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.

Module Fix. The Module Fix moves construction off site. Companies such as Oldcastle Rotondo of Rehoboth, MA, Tindall Corporation of Petersburg, VA, and Rotondo Weirich of Lederach, PA, fabricate single-cell and two-cell prison modules. These modules consist of five or six 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 existing process of building prisons as the contractor would simply purchase the completed prison cells and then lift them into place. This results in higher materials procurement costs and different on-site skill and equipment needs, but it reduces labor risks and associated costs, and it also results in greater quality consistency.

Consideration of Fixes

Table 1 lists the project participants involved in the various fixes that were discussed in this paper and additional ones described by Tsao et al. (2000b). As shown, all project participants are involved in at least one fix. Local fixes are controlled by a single project participant and are feasible within the existing contractual arrangements whereas global fixes are not. Many local fixes fall under the category of "productivity improvement" (e.g., Oglesby et al. 1989) but few fixes are, in fact, local.

A company's ability to recognize and implement a fix is dependent on contractual agreements. For instance, had Spancrete also been responsible for installing the frames, they would have had an incentive to develop a more global fix. The issue thus is: Who owns/controls the supply chain? In this situation, partly because Boldt holds a design/build contract, and partly because Boldt is the construction manager who self-performs a considerable portion of the work, Boldt owns/controls a significant part of the supply chain.

As mentioned, we worked with Spancrete to evaluate the feasibility of the concrete lip fix and the precast fix. We also heard later that Redgranite workers eventually determined how to install security sealant on both sides of the frames to eliminate the need for the plywood fix. As a result, after using the plywood fix primarily in Housing Buildings E and F, workers used the security sealant fix instead in Housing Buildings G and H.

From Fixes to Work Structures

When confronted with problems of an existing system, it is natural to try and develop "fixes" to solve the problems. Consequently, a good way to address problems within a project that has an established product design is to consider fixes to the production system. Then, project participants should consider the feasibility of the fixes to highlight those that have the best potential for successful implementation. With the best fixes in hand, project participants should find good combinations of fixes to form alternative work structures. In general, local fixes are easier to combine to form alternative work structures, while global fixes may be so complex that they can form an alternative work structure in and of their own.

In this case, workers eventually succeeded with the security sealant fix and thereby eliminated many fixes from further consideration. With Boldt's input, we selected a handful of the most promising fixes to be combined into two alternative work structures. The first alternative combines the security sealant fix with the grout pump fix. The grout pump fix replaces a company-owned air-pressure powered grout pump operating at 30 MPa (4,350 psi) that costs $1,200 per month in rent to the project with a hand-operated grout pump operating at 5 MPa (725 psi) that costs $500 to purchase and can last several years depending on use (e.g., Kenrich Products 2002). Boldt tried this low-risk alternative on its next project: It was simple to test and could not significantly impact the project if it failed. After learning to use the hand-operated grout pump, Boldt successfully adopted this alternative work structure.

The second alternative is the precast fix. Recognizing its potential but due to issues brought up earlier, Boldt is continuing to assess its technical feasibility. In addition, Boldt might need to test the soundness of this work structure in order to convince Venture that it is a sufficient, if not a superior, alternative.

Table 1. Fix-Responsibility Matrix

	FIXES	Venture Architects	Boldt Constr.	Spancrete Industries	LaForce Doors	Central City Panel Erection	Jacques Caulking
Prevent Caulking Blowout	Grout Pump Fix[a]		■				
	Security Sealant Fix	▥	▥				■
	Grout Fix[a]	▥	■				
	Foam Fix[a]	▥	■				
	Hydrostatic Pressure Fix[a]		■				
Prevent Grout Leakage	Plywood Fix (Actual Fix)		■				▒
	Bungee Cord Fix[a]		■				
	On-site Weather Stripping Fix		■				
	Off-site Weather Stripping Fix[a]		▥		■		
	Uneven Leg Channel Fix[a]	▥	■		■		
Eliminate Grouting	Pre-Grouted Frame Fix[a]	▥	▒				
	Stacked Pre-Grouted Frame Fix[a]	▥	▒				
	Concrete Lip Fix	▥	▒	■			
	Heavy Gauge Steel Frame Fix	▥	■				
	Weld Plate Fix[a]	▥	■				
Manage Cracks	Field Sequencing Fix[a]	▥	■		▒	▒	▒
	Tolerance Fix		▒	■	■		
Combine Components	Precast Fix	▥	▒	■	▒	▒	
	Module Fix	▥	■	■	▒	■	▒

■ perform fix ▒ work affected by fix ▥ approve fix

[a]Fixes discussed in Tsao et al. 2000.

Integrated Product–Process Design and Design/Build

Work structuring could naturally drive a design/build project, but this is not the way today's design/build projects are conceived. A State project manager noted that Wisconsin's decision to use design/build at Redgranite was driven by the demand for project delivery speed—there has been "overcrowding in the correctional system for a number of years"—however design/build is "not a typical way of doing business with [the State]" (Ryan 2000). The State's chief architect further noted that "the State's primary use for design/build is to quicken a project's timetable in order to squeeze it into the upcoming state budget" and that "the State would be more willing to use design/build on simple projects like… correctional facilities [because] you can describe what you want with a simple building much more easily than you can with a complex building." The Daily Reporter, a newspaper that covers Wisconsin construction, rewarded the State's experiment in design/build by naming Redgranite 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.

Based upon a statistical analysis of 351 U.S. general building projects, researchers found that design/build offers more speed and certainty in cost and schedule performance in comparison to design/bid/build (Champagne 1997; Konchar and Sanvido 1998; Sanvido and Konchar 1998). Reinforcing this finding, Boldt noted that the use of design/build shaved 6 to 9 months off Redgranite's schedule (Thompson 2000). However, our case study revealed that despite the existence of a design/build contract, Boldt and Venture broke up the system of walls and door frames as if Boldt held a design/bid/build contract—Venture designed the components and Boldt installed them.

The need for the plywood fix indicates a lack of product–process design integration. However, installers do not necessarily complain about (deficient) product design because (1) contractually speaking, the original design is given to them and must be executed as contractually agreed upon, (2) at the time of installation, they feel it is too late to get changes made, (3) they worry that by providing a design alternative, they will be considered nonresponsive to the bid request, (4) they do not want to be liable if their suggested design fails, (5) they will lose an opportunity for potentially lucrative changes later, (6) they may have more important problems to address, such as developing bargaining tactics and determining which battles to fight, or (7) site problems may be considered theirs to resolve and complaining might reflect poorly on their skill and pride ("tricks of the trade"), so they believe workarounds are what they are supposed to do. Workarounds are of course costly and time consuming, yet they are an accepted way to perform work.

Wisconsin practitioners have been questioning what it means to use design/build. Snow (2000) suggested that design/build might be "anything the owner thinks it is" while Schultz (2000b) found that all contractors he interviewed had different interpretations of design/build. Doyle (2000a,b) noted that since practitioners have different definitions for design/build; design/build as a concept is hard to define and thus difficult to quantify and measure. Furthermore, design/build takes on many variations (e.g., projects led by contractors, design/build teams, designers, developers, or joint ventures), so we lack a standard framework for design/build implementation (Doyle 2000a; Schultz 2000a). These factors are not endemic to Wisconsin—they are found in numerous other regions that employ design/build. Thus, although design/build serves as a contracting approach and has convinced states to move away from design/bid/build selection of project participants, it only provides an opportunity for collaboration and, as Paulson (1976) pointed out, "[its] name alone, however, does not guarantee results." Instead, work structuring should be developed to provide a framework for collaboration.

Work Structuring Revisited

We advocate the use of an explicit work structuring approach to provide a structured framework that guides project participants toward achieving integrated product–process design. Molenaar and Songer (1998) found that "the percent of design completion at the request for proposal (RFP) phase has no statistically significant effect on project success… Too much design can be constraining and limit the advantage of creativity and constructability in design/build." They further noted that "an RFP that clearly defines the project scope but leaves room for contractor input will be most successful." Along the same lines, work structuring should be first addressed early in the AEC project development process before any major decisions in product and process designs have been made. For example, project participants may meet at the project onset to develop a "schematic design in a day" to investigate a range of alternative work structures (Miles 1998). In addition, if project participants had access to information about the work structures used on similar past projects, then the five whys could be employed to identify ways to improve upon their performance.

Some may argue that the cost of the system of walls and doors is small in relation to the overall project, so it is wasteful to investigate improvements to its delivery. However, as mentioned, the system of walls and doors is critical in prison construction because it generates value for the owner. Moreover, in addition to the benefit of reducing the project's duration, our analysis revealed that Boldt could save on the order of $100,000 on each project by implementing changes such as the precast fix.

Accordingly, we advocate that all project participants systematically address work structuring issues at varying levels of detail during coordination meetings so that several systems solutions will be developed and considered. During these meetings, a different person could be appointed each time to make work structuring issues transparent for the group. This work structuring facilitator would be responsible for identifying and documenting any tradeoffs that emerged between the project's supply chain, product, process, and operations designs. This transparency could help the group better understand the implications of their design decisions. In addition, having different facilitators engages more project participants in the work structuring effort and is likely to foster a more collaborative environment in the project development process. Alternatively, the owner could ask one of its representatives to be the facilitator.

Is the plywood fix representative of today's construction practices? We believe it does reflect today's reliance upon on-site craft skills to mitigate problems that should not have been created in the first place. The companies involved in this case study are well regarded in their fields, so their practices are "typical" if not better than the industry average. Engineering News Record (ENR) lists Boldt as No. 109 of the 2001 Top 400 Contractors (ENR 2002) and Venture as No. 97 of the Top Midwest Design Firms (Midwest Construction 2002). Boldt's and Venture's combined experience in prison construction was used when they designed and built Redgranite in a fashion similar to before. The owner, designers, and wall fabricator balanced their needs and resources to develop the product design. The panel erectors, door frame installers, grouters, and caulkers negotiated their traditional work procedures to develop the operations design. However, since all project participants rarely have the opportunity to consider the structure of work together and early enough to decide what would work best for the system, the product design was developed with little consideration for the process design. As a result, project participants were more product than systems oriented, so the system of walls and door frames at Redgranite was far from optimal.

Work structuring includes elements from various practices in the AEC industry, such as constructability analysis, value engineering, and productivity improvement studies. However, despite the extensive literature on these subjects, we are unaware of any documents that present these practices formally to achieve systematic implementation. Like design/build, they have difficulty developing solutions beyond contractual agreements, work traditions, and trade boundaries because they try to preserve standard work breakdowns and traditional roles of supply chain participants. As a result, these practices fail to recognize opportunities for systematic improvements that arise from the definition of work structuring proposed in this paper.

Work structuring aimed at project-level performance may have been employed by others on previous projects, possibly by engineer–procure–construct companies. However, even then, it is likely those projects structured work in an ad hoc fashion because we have yet to see the theoretical concepts of work structuring formulated for application in the AEC industry and discussed in technical journals. Should work structuring be well established in practice, then our role as researchers is to document the instances of practice to support and validate its emerging theoretical principles (Laufer 1997). After describing and validating the work structuring theory, we should articulate techniques for effective work structuring. However, we suspect that most projects do not systematically structure work, so we hope that our research effort in documenting the presented case study will convince AEC practitioners to consider work structuring on their projects, and educators to introduce it in their teaching.

Conclusions

The hollow metal door frame case study illustrated a typical problem encountered in AEC practice today, where a contracting mentality hampers thinking about system-wide production-based solutions. We revealed how poorly-made decisions resulted in lost opportunities for achieving systematic improvements. On this project, the architect decided on the work structure by designing the system of walls and doors. The wall fabricator and door frame manufacturer together might have developed a better system design, had they not been restrained contractually by each getting a piece of the work from the construction manager and provided they could resolve design liability issues.

This case study leads to the following conclusions about work structuring and integrated product–process design practice: (1) The use of design/build project delivery does not ensure integrated product–process design. Although Redgranite was praised as an outstanding design/build project, we identified lost opportunities to improve the design and construction of one of its primary systems. (2) Traditional WBS practice prevents project participants from seeing opportunities for systemic change. The architect is accustomed to designing walls and door frames separately. The construction manager is accustomed to procuring walls and door frames separately. The company that makes walls is different from the company that makes doors. As a result, project participants failed to see the walls and door frames as a single enclosure system that generates significant value for the owner. (3) Local optimization can be detrimental to global optimization. As latex caulking is cheaper than security sealant, the construction manager first asked to change the caulking requirements to reduce materials costs. The construction manager thereby unintentionally contributed to grout blowout problems. (4) Project participants fail to learn across projects; they rely on "received traditions" (Schmenner 1993, p. 399). Installers may not see that process design problems can be linked to inadequacies in product design. Thus, they do not provide feedback to designers to encourage modifications of the product design to better support process design.

To summarize, this case study has described problems the construction crews faced, examined solutions they came up with, and explored systems design decisions that shaped operations design. We illustrated the kind of reasoning that is needed to engage in work structuring, applied the five whys to get to root causes of problems within the existing work structure, and demonstrated how project participants can develop alternative work structures. We provided some theoretical underpinnings of work structuring and advocated the use of work structuring to serve as a framework for achieving integrated product–process design. Over 30 years ago, a contractor noted "the need for removing the legal, social, and labor restraints presently burdening the construction industry" (Kellogg 1971). We believe making work structuring explicit can help practitioners overcome these constraints and adopt better ways of designing and building projects.

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