APPLYING A SET-BASED DESIGN APPROACH TO REINFORCING STEEL DESIGN

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ABSTRACT

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Researchers and practitioners have been implementing ‘lean’ in the architecture engineering construction (AEC) industry since the 1990s. They seek to bring lean practices from the manufacturing and new product development communities, most notably those developed by Toyota, to the AEC industry in support of improved project delivery. Toyota engineers use a set-based design methodology to promote innovation in product design, reduce rework, and facilitate collaboration between project stakeholders. AEC practitioners use a set-based design methodology to some degree; however, it has not been formalized nor has implementation been widespread.

The set-based design methodology involves postponing commitment to a specific design, instead generating and evaluating sets of design alternatives. A design team reviews the sets of design alternatives available to each project stakeholder and integrates them to find compatible combinations. They weigh input from several project stakeholders at the same time, early on, and throughout project delivery, while studying tradeoffs between what individual stakeholders value and what is of value to the project as a whole. Set-based communication helps stakeholders avoid rework and, through teamwork, develop a more globally satisfactory design than would otherwise be the case.

This dissertation argues for the use of a set-based design methodology in the AEC industry and presents tools and processes that could aid in its implementation. It specifically explores the use of a set-based design methodology to select reinforcing steel (rebar) configurations for reinforced concrete projects through case studies and workshops. Moreover, it examines the role of the design structure matrix (DSM) in revealing opportunities for implementing a set-based design methodology and explains the role of the Choosing By Advantages Decisionmaking System (CBA) in a set-based design methodology.

Research findings illustrate the effectiveness of set-based design in reducing rework and facilitating innovation on AEC projects. No single set-based design methodology will apply to all projects: opportunities for implementation vary from project to project. This dissertation delivers a proof of concept for a set-based design methodology and validates it through case studies and workshops. Future research can deepen the theoretical understanding of set-based design methodologies and further advance tools to support it in the AEC industry.

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DEFINITIONS

Concept	Definition
Artifact or Product	Something sold by an enterprise to its customers (Ulrich and Eppinger 2004).
Concurrent Engineering	The *simultaneous* co-development (co-design) and integration of product and production system enabled by the application of historical and/or exchanged multidisciplinary capability information.
Choosing By Advantages	A decision-making system that supports sound decision-making using specific comparisons of advantages of alternatives (Suhr 1999)
Design or Design Process	A "systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy stated constraints" Dym and Levitt (1991).
Design Structure Matrix	A representation and analysis tool for system modeling, especially for the purposes of decomposition and integration. Originally developed by Steward (1981), a square matrix denotes project activities and related interdependencies. The activities are then re-sequenced and redefined through partitioning and tearing (Browning 2001, Ulrich and Eppinger 2004).
Design Team	Architects, engineers (structural, mechanical, electrical, HVAC, etc.), designers, managers, and contractors arranged to provide design services on a specific project.
Engineering	A profession concerned primarily with the application of a certain body of knowledge, set of skills, and point of view in the creation of devices, structures, and processes used to transform resources to forms that satisfy the needs of a customer or society (Shigley 1996, Ulrich and Eppinger 2004).
Flow View	Describes design as the flow of information or material, which goes through transitions, moves, and waiting. This description focuses on removing the waiting time (non-value added time) associated with each flow (Koskela 1992).
Framework	A conceptualization of a process which can incorporate multiple theories or research findings. (Waldron and Waldron 1996)
Lean Management Philosophy	Production system management based on the integration and balancing of TVF theory conceptualizations.
Iteration	The process of repeating nominally complete activities (Ulrich and Eppinger 2004).
New Production Philosophy or TVF Theory	View of production based on the integration of the Transformation, Value, and Flow views (Koskela 1992).

Owner or Customer	The organization in an AEC production system that is primarily responsible for establishing project criteria, validating and translating user needs, and providing financing.
Point-Based Design	Point-based design involves selecting a single structurally-feasible design alternative that meets project requirements at each step in the design process and then refining that single design (or point) while developing more details during the design process. This single design is then re-worked until a solution is found that is feasible (Parrish et al. 2007).
Product Development	The set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product (Ulrich and Eppinger 2004).
Production	“The designing and making of artifacts” (Ballard 2000a).
Project Stakeholders	Those members of the supply chain that would be directly impacted from a change in design methodology.
Rework	Unplanned iteration in the design process due to quality or constructive deficiencies (adapted from Ballard 2000c).
Set-Based Design	“Designers explicitly communicate and think about sets of design alternatives at both conceptual and parametric levels. They gradually narrow these sets by eliminating inferior alternatives until they come to a final solution” (Ward et al. 1995).
Supply Chain	A network consisting of “suppliers, manufacturing centers, warehouses, distribution centers, and retail outlets, as well as raw materials, work-in-process inventory, and finished products that flow between the facilities” (Simchi-Levi et al. 2003).
Theory	The linkage between a phenomena of interest and the factors affecting that phenomena (Whetten 1989).
Transformation View	Design is the process of transforming functional requirements into a set of specifications and drawings to define a product design (Koskela 1992)
User Needs	The characteristic valuable attributes of a project described by facility users.
Value View	Design is a process where value for the customer is created by meeting the functional requirements of the owner, user, or both (Koskela 1992).
Work Structuring	The effort to develop a project’s process design while trying to align engineering design, supply chain, resource allocation, and assembly efforts (Tsao et al. 2000).

ACRONYMS

AEC: Architecture Engineering Construction

BIM: Building Information Model

CBA: Choosing By Advantages

CRSI: Concrete Reinforcing Steel Institute

DSM: Design Structure Matrix

DTM: Design Theory(ies) and Methodology(ies)

ETO: Engineered-to-order

IFOA: Integrated Form of Agreement

IPD: Integrated Project Delivery

MEP: Mechanical-Electrical-Plumbing

RFI: Request for Information

CHAPTER 1. INTRODUCTION

1.1 INTRODUCTION

Reinforced concrete is used on many construction projects throughout the United States. Many specialists are involved in the reinforced concrete supply chain, including structural engineers, general contractors, steel reinforcing bar (rebar) fabricators, inspectors, laborers, formwork contractors, and others. All affect each other in one way or another, yet there is seldom much interaction between them before concrete is placed onsite due to contractual relationships. Lack of communication often leads to problems onsite, and can lead to significant rework, both in design and in construction. Rework can be caused by owner changes to design, faulty placement onsite, failure to pass permitting or inspection requirements, etc.

Early collaboration between parties has been effective in reducing the amount of rework necessary. Researchers and practitioners alike are trying to develop new processes of design and construction that promote early collaboration and reduce clashes and congestion onsite. This research suggests collaboration is most effective if the parties collaborating can share incomplete information and have incentives to do so. Project teams may be unaccustomed to sharing information before it is complete, but doing so well allows project stakeholders to develop solutions together, which often leads to benefits for the project (Lichtig 2005b; Mikati et al. 2007; Parrish et al. 2008a).

This dissertation focuses on set-based design, a method that uses collaboration amongst project stakeholders to develop more globally satisfactory design solutions. A set-based methodology for rebar design is developed, drawing on knowledge and principles of new product development, where set-based design has been successfully implemented.

1.2 BACKGROUND

Concrete "has high compressive strength and low resistance to tension:… its tensile strength is approximately one-tenth of its compressive strength" (Nawy 2000). Thus, plain concrete is reinforced with steel bars, rebar, to give the composite material more tensile strength. When designing a concrete member, the objective is to maintain equilibrium in the member; that is, to maintain equality of the compression force provided by the concrete with the tensile force provided by the rebar. Rebar confines the concrete core of a member, i.e., it restrains lateral movement of the concrete. Adequate confinement is necessary to "ensure that the flexural capacity of the members can be developed without deterioration… under repeated loadings" (ACI 2005), and therefore becomes extremely important when considering structural performance, e.g., in the event of an earthquake.

1.2.1 REINFORCED CONCRETE DESIGN

The reinforced concrete design process is "a sequential and iterative decision-making process" (MacGregor and Wight 2005, p. 12). It consists of three broad steps: (1) calculating design loads, (2) selecting a structural system to resist them, and (3) designing and detailing members of the structural system. Building codes and permitting agencies "govern" reinforced concrete design to ensure public safety. Most jurisdictions within the United States adopt the American Concrete Institute's (ACI) *Building Code Requirements for Structural Concrete and Commentary,* published by ACI Committee 318, as a basis for granting building permits (ACI 2005). Most jurisdictions permit engineers to develop non code-compliant structures if the engineer proves the structure will perform in a manner that meets public safety standards.

Figure 1 schematically shows the process for reinforced concrete design. Structural engineers calculate design loads according to ASCE-7, a standard published by the American Society of Civil Engineers (ASCE 2005), or another regulatory document. Based on load effects, and so-called ‘design heuristics’ (e.g., experience, rules-of-thumb, intuition) the engineer selects a structural system and develops a trial design. The engineer “tests” this trial design either through procedures outlined in codes, experimental testing, analytical modeling, or a combination thereof. The engineer accepts or rejects the trial design based on its compliance with local building codes, its performance in experimental testing, or both. If the engineer or another governing body (typically the local building permitting agency) deems the trial design unacceptable, the engineer develops a new trial design. Once the engineer and governing body accept the trial design, detailing begins for the first time. Detailing consists of sizing members, specifying a concrete mix design, and detailing rebar configurations (selecting rebar sizes, shapes, spaces, splices, etc.).

To detail rebar, structural engineers calculate a required rebar area, A_s, based on design loads or the reinforcement ratio, ρ, that compares rebar area, A_s, to the gross area of the concrete section, A_g. The American Concrete Institute requires that ρ be between .01 and .08 (ACI 2005). These bounds maintain resistance to bending and constructability (in this context, constructability means providing room for concrete to flow between rebar), respectively. Given this area (A_s), structural engineers design rebar layouts for each alternative to achieve code-mandated strength and ductility each member.

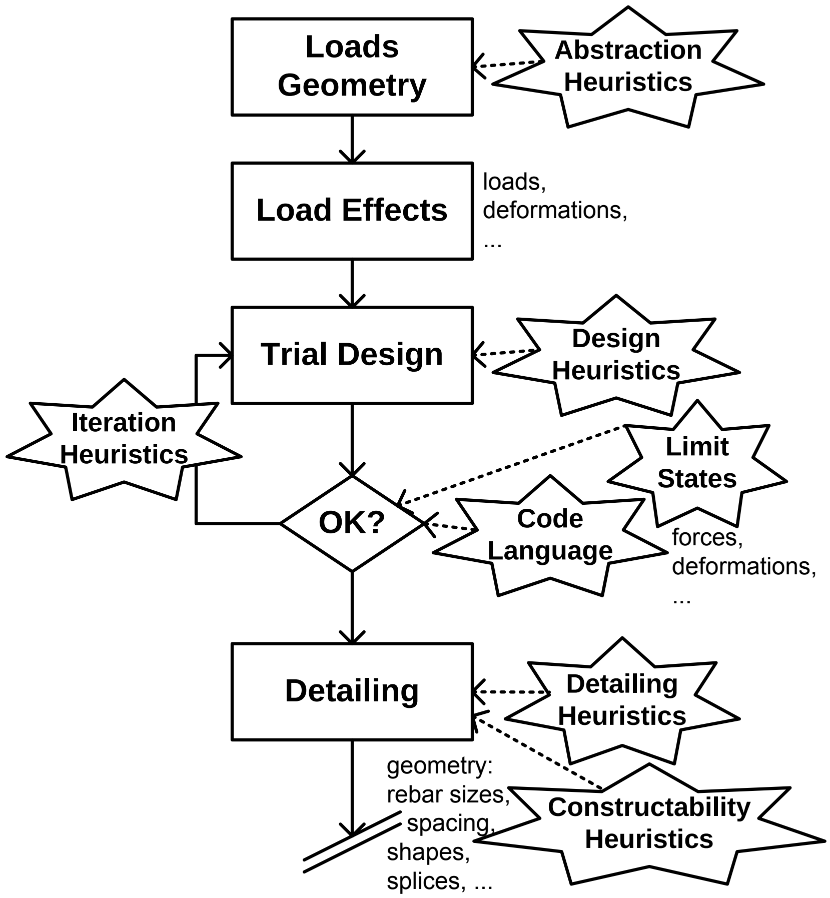


Figure 1. Reinforced concrete design process and heuristics (Tommelein et al. 2005)

1.2.1.1 Standard Rebar Design Practice (Point-Based)

Given the reinforcement area (A_s) necessary to achieve the mandated strength and ductility, a structural engineer chooses a specific rebar configuration (bar sizes and layout) to meet the calculated demand. The engineer's experience and rules of thumb inform this choice. A specific rebar configuration is a choice of the structural engineer; while multiple rebar configurations may meet the demands, typically, the contract requires the structural engineer to specify *one* configuration. As long as a member meets the area and spacing requirements mandated by the governing structural code (e.g., ACI 318 (2005) or is approved by the local permitting agency, that member is said to be structurally sound.

In a competitive bid environment—today's standard practice—a structural engineer is typically hired by an owner or an architect to design a structure before the owner has selected the entire project team. So, the structural engineer designs the structure by known or preferred means to meet the criteria identified during design (i.e., design loads, project cost, space and layout requirements, and structural functionality). Often, architects provide structural engineers with building shape and general building layout. Geotechnical engineers give structural engineers a geotechnical report detailing logs from soil borings and possibly a characterization of the entire site. A structural engineer may design a reinforced concrete structure to be least weight, least floor-to-floor height, or optimized using other criteria. The current cost paradigm in the structural engineering community is: "less material leads to less cost." Considering only materials, this is true. However, if one considers labor costs as well, it may be more cost effective to use more material in order to reduce labor costs. For instance, labor costs for placing a greater number of lighter pieces are often higher than those for placing a smaller number of heavier pieces.

"Over the wall" designs are characteristic of the point-based design methodology. That is, point-based designs are typically optimized locally, and modified sequentially throughout the design process. Figure 2 illustrates point-based design, consisting of selecting a single design (or a point), then improving on it as more details become available.

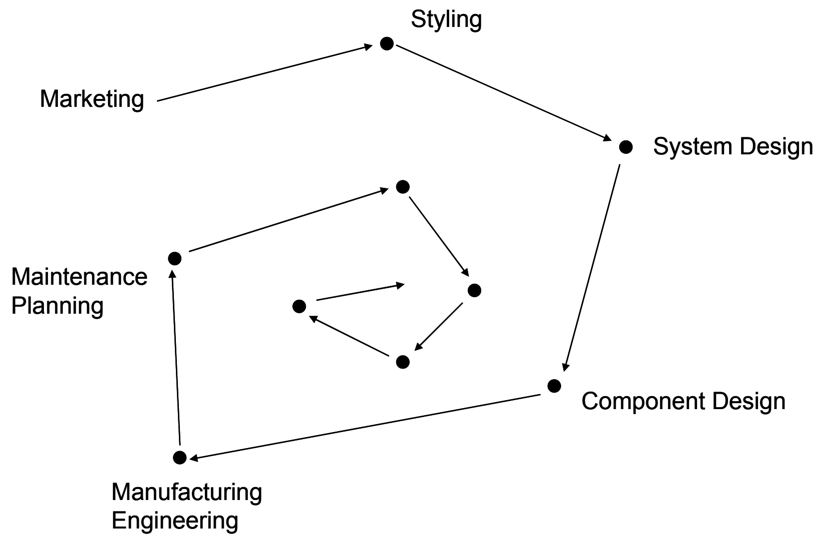


Figure 2. Point based design process (Figure 2 in Ward et al. 1995)

Figure 3 illustrates design process phases and final decisions at the end of each phase. The 'Final Decisions' boxes state the decisions necessary to release work for the next phase of design. The 'Project Team Collaboration' boxes address tasks the team discusses during a given design phase, highlighting the need for collaboration throughout the project.

The primary goal of the Programming Phase is to articulate and understand the functional requirements of the structure being designed. Typically, at this phase, the project team consists of the owner, the architect, and possibly an engineer and a general contractor (GC) who offers preconstruction services (e.g., preliminary schedule development, constructability reviews, etc.). The owner articulates the functional requirements, purpose, and intended use for the structure. The architect formulates these into design criteria and then develops viable design alternatives to meet them. The owner also determines the project scope, budget, and schedule during this phase. By the end of the Programming Phase, the owner determines the contract type, finalizes how the project will be financed, and locks in milestone schedule dates.

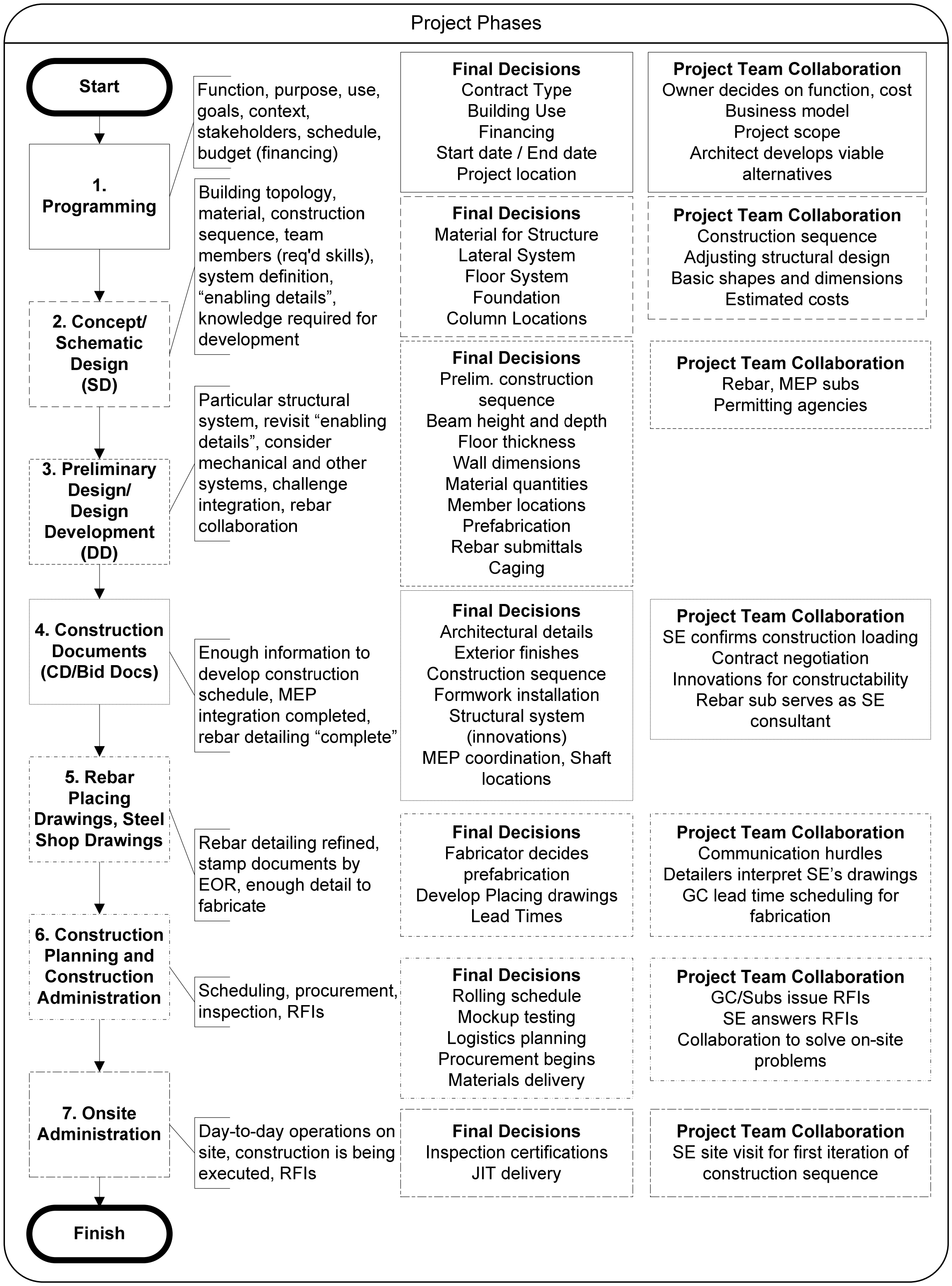


Figure 3. Project phases and decisions in the current state of the design process

Once programming is complete, Concept/Schematic Design (SD) begins. During SD, the structural engineer (SE) develops schematic structural designs for the architects' design alternatives (developed during Programming). Schematic designs may take the form of sketches, three-dimensional models, or even simple word descriptions. Typically, the project team consists of the owner, the architect, the structural engineer, and possibly a pre-construction general contractor and specialty engineers (e.g., MEP engineers). As the project team develops the architect's alternatives throughout the SD phase, they identify 'enabling details' for the project, i.e., the details necessary for the project to move forward (e.g., appearance, construction sequence, prefabrication, etc.) and knowledge required to complete the project (e.g., results of experimental testing, specific subcontractors, etc.). The project team begins to discuss the construction sequence and the basic shapes and dimensions of the structure to facilitate a cost estimate. By the end of this phase, the team agrees on the building material, the lateral and floor systems, the foundations, and the column locations.

Upon completion of SD, Preliminary Design/Design Development (DD) begins. During DD, the owner may begin to hire the construction team for the project, growing the project team already in place through SD. During DD, the structure literally begins to take shape, as the project team details it. Decisions made during this phase include the preliminary construction sequence, beam and column height and depth, floor thickness, wall dimensions, material quantities, and member locations. The construction team also makes decisions about prefabrication. The rebar subcontractor submits placing drawings and determines whether or not cages will be prefabricated or built onsite. The project team begins to check the design for clashes between trades and may begin discussions with the permitting agencies about the design.

Following DD, the Construction Documents (CD) phase begins. During the CD phase, the project team develops the design to the level of detail necessary to develop a construction schedule. The project team collaborates during this phase to improve the design's constructability if possible. They may also negotiate contracts during this phase, especially clauses relating to material cost escalation. Also, the structural engineer works with the construction team (if known) to confirm and approve construction loading. By the end of this phase, the project team confirms architectural details (e.g., awnings, façades, etc.), exterior finishes, the construction sequence, formwork installation plans, structural system details, and final MEP coordination, including shaft locations.

Once the project team develops construction documents, the Rebar Placing Drawings phase begins. This phase involves the owner, the architect, the structural engineer, the general contractor, and the rebar subcontractor. The rebar subcontractor develops rebar details, so-called placing drawings, based on the structural drawings completed during CD. Rebar subcontractors use placing drawings to develop a rebar fabrication and installation schedule. The structural engineer of record (EOR) reviews these placing drawings. The detailer and the EOR collaborate to develop details that meet the EOR's approval. The EOR stamps this set of placing drawings. The rebar installation schedule includes lead times and informs the GC's construction schedule.

Upon completion of the Rebar Placing Drawings phase, Construction Administration begins. Construction Administration incorporates the startup of the construction phase. During Construction Administration, the construction team issues requests for information (RFIs) to the design team as needed. The design and construction teams collaborate to solve onsite problems that may arise as construction begins. The project team makes decisions about material procurement, logistics, and delivery. They also build any mockups necessary during this phase.

Finally, the project team enters the Onsite Administration phase of the design process, which consists of managing day-to-day operations onsite. RFI submission continues through this phase, and the SE visits the site to approve the first iteration of the construction sequence (typically an iteration includes the construction of at least one wall and one floor). Decisions made in this phase include inspections and the material delivery schedule.

In a structural engineering office, point-based design may consist of an engineer selecting specific T-heads to anchor rebar in a beam-column joint (rather than hooking the bars back into the joint). Indeed, one structural engineer interviewed in the course of this research described a case where she had specified “Headed Reinforcement Corporation (HRC) T-heads or equal” as terminators for rebar in a beam-column joint for a project in the San Francisco Bay Area (Razzano 2008). When the rebar subcontractor joined the project team, he requested a substitute T-head to avoid sending the bars to Los Angeles (LA), CA to have the T-heads installed (HRC requires T-heads be installed in their LA facility). The substitute T-heads could be installed in the subcontractor’s shop, because they had invested in the tools and equipment to do so, thus eliminating the time and cost necessary to transport bars to LA for T-head installation. The structural engineer needed to determine whether or not the alternate T-heads were “equal” to the HRC T-heads. She reviewed the specifications for the substitute T-heads, verified they provided the same strength as the HRC T-heads, and approved the substitution. Had she been aware earlier in the process of the need to transport bars to LA for T-head installation, she may not have specified those T-heads. Chapter 2 presents an example comparing decision-making systems to choose a rebar terminator.

This is a classic point-based design example, where an initial design represents a *feasible, but locally optimized* solution. This design may be modified to develop a more globally satisfactory design; however, the initial design must be reworked to accommodate the values of the project team (in the case of the example, the team included the owner, architect, structural engineer, general contractor, and rebar subcontractor), because the initial design was not necessarily informed by the project team.

1.2.1.2 Set-Based Alternative for Rebar Design

Collaborative design methodologies that involve the project supply chain (owner(s), architects, engineers, suppliers, builders) from the beginning of a project develop better products, in terms of quality, cost, and time to market (Liker 2004; Liker et al. 1996; Ward et al. 1995). One such methodology is set-based design (Sobek II et al. 1999; Ward 1989; Ward et al. 1995), which considers sets of design alternatives rather than a specific design (or point) during the design process. In a set-based design environment, a work structuring effort would determine the stakeholders relevant to the design decisions made at each phase of the project at the project outset (these stakeholders would be a subset of the project supply chain participants mentioned in Section 1.1). A project team may initially consist of the owner, architect, structural engineer, and general contractor. As the project progresses and alternatives become more detailed, subcontractor input about their capabilities, material availability, and the design's constructability also becomes available for making design decisions (illustrated in the 'Final Decisions' boxes in Figure 3). Thus, as the project progresses, different stakeholders engage in design conversations.

Figure 4 shows how this set-based design process is carried out. First, the structural engineer performs calculations to determine the set of possible reinforcement alternatives (labeled 'All Alternatives'). Then, the structural engineer and relevant stakeholders apply the 'must' criteria (refer to section 2.4.2), including code requirements, cost constraints, and fabrication capabilities, to reduce the initial set to a set of feasible reinforcement alternatives (this set could take the form of a bounded rebar area for a given concrete member or a discrete set of configurations that meet the 'must' criteria). The circle, triangle, and square that appear below the 'Must Criteria' line represent this feasible set. Relevant stakeholders provide their expertise to the designer, including information about rebar availability, prefabrication opportunities and costs, rebar placing and material costs, and placing preferences (a 'want' criterion, refer to section 2.4.2). Based on this information, the team selects a mutually agreeable rebar configuration (denoted 'Solution'). Generally this will not be more satisfactory for the project stakeholders than the configuration selected without the input of downstream stakeholders.

1.2.2 STRUCTURAL ENGINEERING CODES USED IN THE UNITED STATES

For a structure to be built, the project stakeholders must obtain permits for it. Thus, one 'must' criterion on every project is "The structure must be approved by the local building department." Therefore, the requirements from relevant structural engineering codes, or the code(s) adopted by a jurisdiction, also are 'must' criteria.

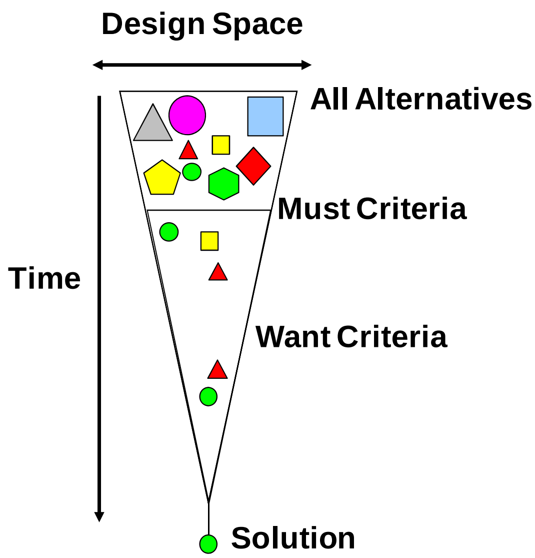


Figure 4. Set-based design process

In the United States, most cities, counties, and states have adopted the International Building Code, IBC 2006. This code replaced the Uniform Building Code (UBC) 1997 in California effective January 1, 2008 (International Code Council 2008a). Accordingly, all plans submitted for permit review in California on or after January 1, 2008 must comply with IBC 2006 (California Architects Board 2008). Unlike the UBC, which specifically listed all requirements for structures, the IBC references other codes. ACI 318 (ACI 2005), *Building Code Requirements for Structural Concrete and Commentary*, is the reinforced concrete design code referenced. In California, an area of high seismicity, Chapter 21 of ACI 318 governs most concrete design. "Chapter 21 contains special requirements for design and construction of reinforced concrete members of a structure for which the design forces, related to earthquake motions, have been determined on the basis of energy dissipation in the nonlinear range of response" (ACI 2005, p. 307).

Prior to 2000, structural design in California, along with most other states on the West Coast, was governed by the UBC 1997 code. At that time, most structural design in the

Northeast was governed by the Building Officials and Code Administrators (BOCA) National Building Code 1996, and design in the Southeast was governed by the Southern Building Code Congress International (SBCCI) Standard (Southern) Building Code 1999. However, in 1994, “The International Code Council (ICC) was established… as a non-profit organization dedicated to developing a single set of comprehensive and coordinated national model construction codes” (International Code Council 2008b). Figure 5 shows the IBC adoption map, illustrating the widespread use of the IBC 2006 code. By the end of 2008, most of the United States had adopted IBC.

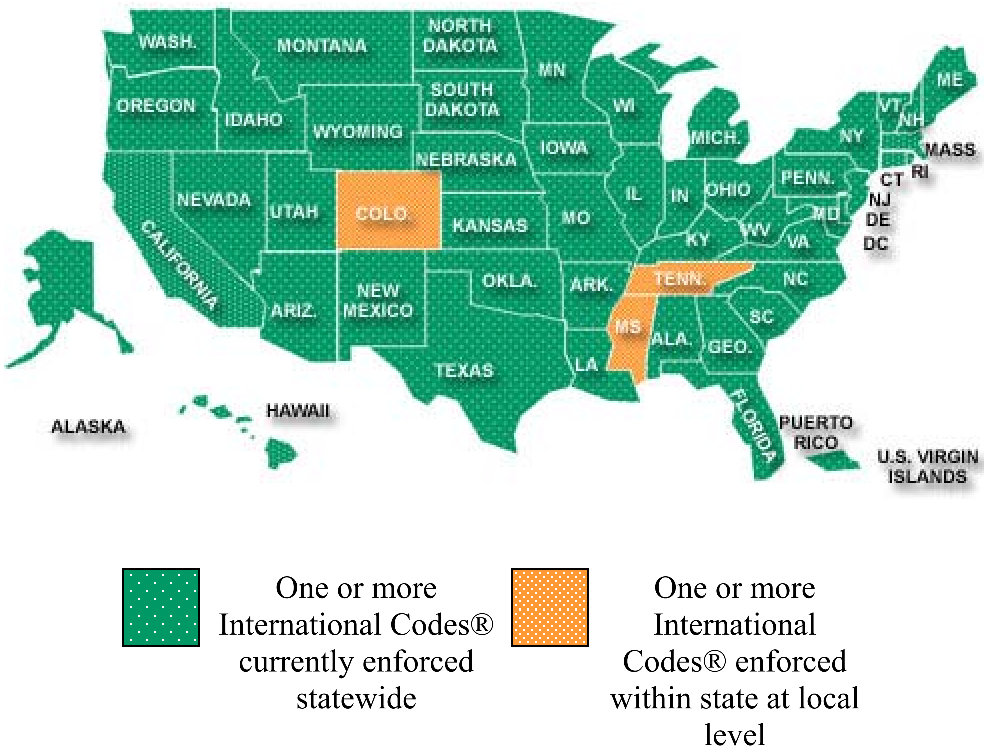


Figure 5. IBC adoption map (International Code Council 2008a)

1.2.3 CURRENT STATE OF THE INDUSTRY

Structural engineering codes provide requirements that design alternatives must meet. While they provide guidelines for the design artifact, they do not prescribe a design methodology. Thus, the author and one of her colleagues, Dr. Stanislaus Tuholski, sent a questionnaire to practicing structural engineers and engineering faculty to determine what methodologies are currently in use for reinforced concrete design (see Chapter 3). Engineers surveyed supported the hypothesis that engineering practice can be characterized as point-based design. Many recognized shortcomings thereof, expressed frustration with this status quo, and expressed an interest in streamlining the structural design process. One engineer said "Structural design is a spiral. You make a start at something based on engineering judgment, you do some analysis that makes you rethink it and you get a little closer to the best answer… sometimes you never get to the center" (P^2SL 2007). Another said, "optimization of the design resources and processes would result in more uniform and cost effective designs" (P^2SL 2007). Another stated, "Design theory ought to be… [focusing on] how… groups of people work efficiently and creatively towards a common goal" (P^2SL 2007), and "I think studying team interactions, especially with consulting peers… would be a great benefit" (P^2SL 2007). The Engineering News Record also reported on the need to change the design process (Buckley 2007).

1.2.4 Lean Project Delivery

Researchers and practitioners in the AEC industry recognize the need to reform the design and construction processes to improve AEC project delivery. Some advocate adopting 'lean' principles from the Toyota Production System (TPS) to improve project delivery. They study TPS in order to find underlying principles that can be employed in their own research and industry (Ward et al. 1995).

The International Group for Lean Construction (IGLC), formed in 1993 (www.iglc.net), followed by the Lean Construction Institute (LCI), established in 1997 (www.leanconstruction.org), advance lean construction theory and promote its application in the AEC industry. Subsequently, the University of California, Berkeley established the Project Production Systems Laboratory (p2sl.berkeley.edu) in 2005 to "develop and deploy knowledge and tools for the management of project production systems and the management of organizations that produce and deliver goods and services through such systems" (P2SL 2009).

The application of lean principles across projects has lead to the development of the Lean Project Delivery System™ (Ballard 2000b). Figure 6 shows the Lean Project Delivery System™, which synthesizes development, design, manufacturing, and operations, recognizing that there is significant overlap in these traditionally separate phases (Pietroforte 1997, Figure 7). This research focuses primarily on the design phase of a project, but it encompasses all triangles in the Lean Project Delivery System™. For instance, set-based design involves stakeholders concerned with Lean Assembly in the design process and draws on their expertise to develop a design that can be pre-fabricated.

The application of lean principles in the AEC industry, such as pull scheduling (Tommelein 1998), reliable promises (Ballard 2000a), and work structuring (Tsao et al. 2000) have led to improved project performance and time and cost savings. Lean construction is being adopted by owners and contractors with great success (Mikati et al. 2007; Plue 2007). Lean design offers a similar opportunity, not only for time and cost savings (Ballard 2000c), but more importantly, for value generation, and is therefore explored in this dissertation.

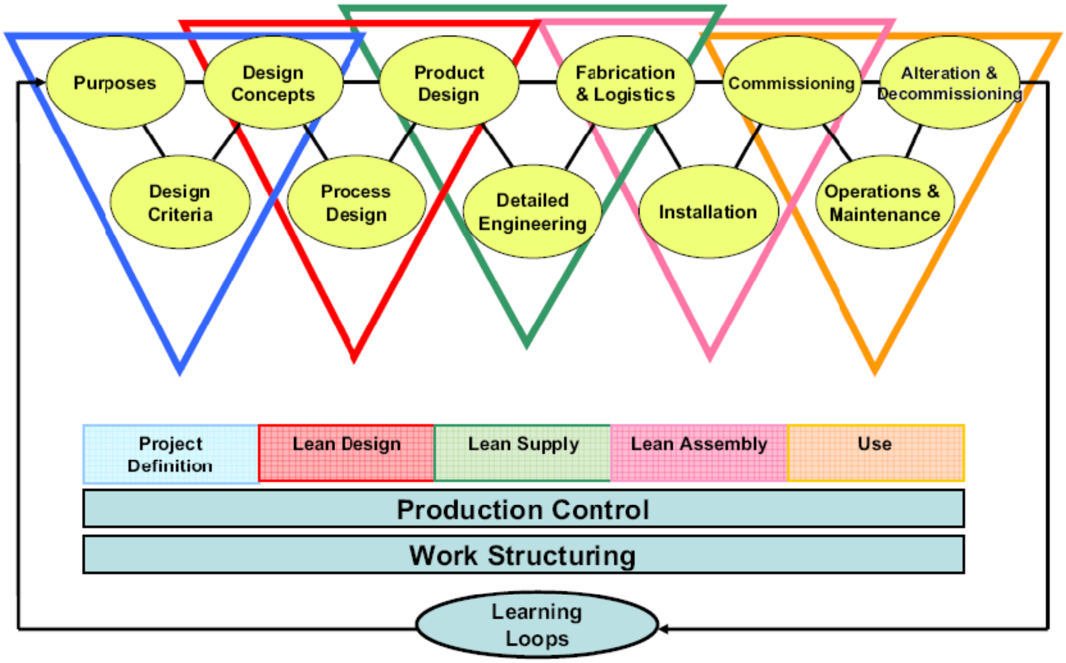


Figure 6. The Lean Project Delivery System™ (Ballard 2000b)

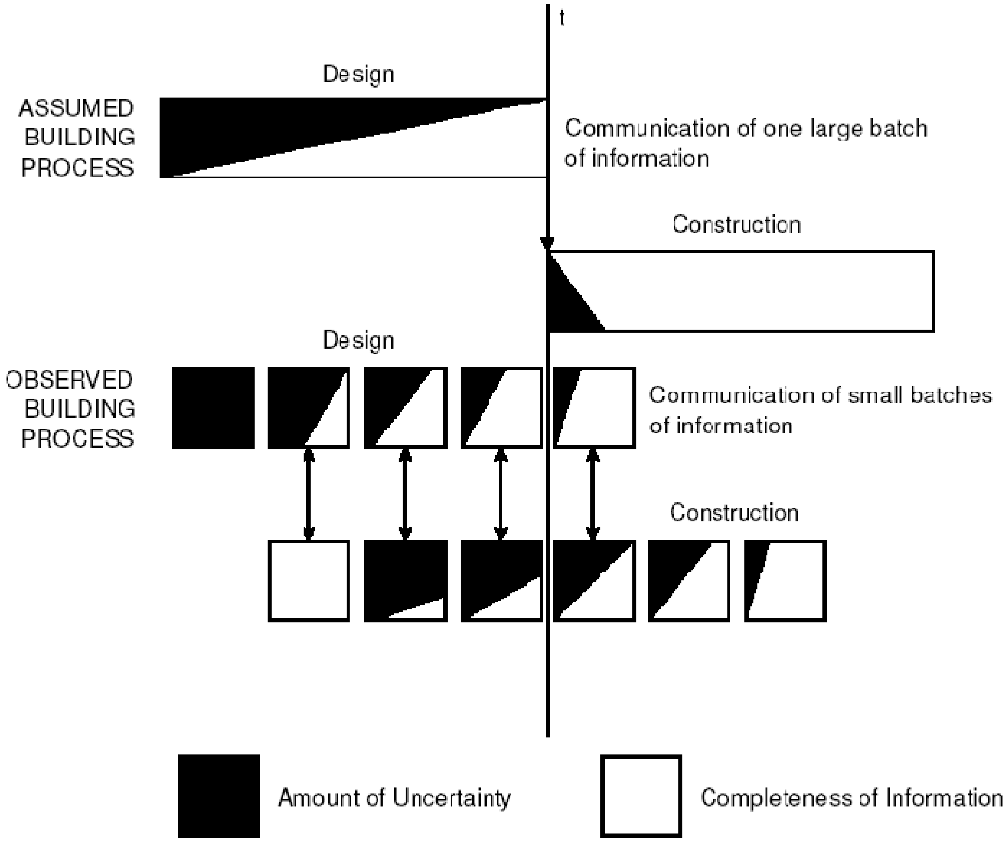


Figure 7. Communication in the building process (Figure 3 in Pietroforte 1997)

1.3 RELEVANCE

1.3.1 DESIGN THEORY

Despite growing interest in the topic of lean, the author found little literature about the theory behind the rebar design process (why is it done the way it is?). Koskela (1999, p. 1) explains the need for theory [in design]:

> A theory provides an explanation of observed behavior, and contributes thus to understanding. A theory provides a *prediction* of future behavior. On the basis of the theory, tools for analyzing, designing and controlling can be built. A theory, when shared, provides a common language or framework, through which the co-operation of people in collective undertakings, like project, firm, etc., is facilitated and enabled. A theory gives direction in pinpointing the sources of further progress. A theory can be seen as a condensed piece of knowledge: it empowers novices to do the things that formerly only experts could do. It is thus instrumental in learning. When

> explicit, it is possible to constantly test the theory in view of its validity. Innovative practices can be transferred to other settings by first abstracting a theory from that practice and then applying it in target conditions.

Cross, quoted in Wynn and Clarkson (2005), defines the field of Design Theory Methodology (DTM) research as:

> The study of how designers work and think; the establishment of appropriate structures for the design process; the development and application of new design methods, techniques, and procedures; and reflection on the nature and extent of design knowledge and its application to design problems.

Theory about rebar design and delivery may provide a theoretical framework for other Engineered-to-Order (ETO) product design and delivery. Furthermore, the AEC industry is changing as Building Information Modeling (BIM) tools offering increased capabilities and design practices are rethought to support more efficient design and delivery methods. Theory can reveal causal relationships in the AEC industry, providing practitioners information to determine the effects of process changes.

1.3.2 ENGINEERED-TO-ORDER PRODUCTS

Many products used in capital projects are Engineered-To-Order (ETOs). Rebar assemblies, structural steel systems, and most precast concrete elements are examples of ETO products. ETOs have a characteristically long lead time. Elfving (2003) defines ETO products as those with "customer orders… processed through engineering, fabrication, and delivery." They are characterized by a long lead time and an early customer order decoupling point (CODP). The customer order decoupling point is the point where the customer interacts with the production system, separating customer-order driven activities from those driven by planning (Wortmann et al. 1997). Figure 8 shows COPDs for various types of products. After the COPD, production can be scheduled to meet *real* demand, but before the COPD, production schedules reflect *speculative* demand.

Lean principles advocate pull systems, or production systems designed for continuous flow. Tommelein (1998) defines a “pull-driven” approach as one whose purpose is:

> To produce finished products as optimally as possible in terms of quality, time, and cost, so as to satisfy customer demand. Achieving high process throughput while minimizing operating expenses including in-process inventories is key… To pull means that resources must be selectively drawn from queues – so the activity that processes them will be busy just the same – but chosen so that the activity's output is a product needed further downstream in the process, and needed more so than its output using other resources in the queue would have been.

Rebar is an ETO product: the customer and requirements set for the delivery of a specific project drive most activities through the supply chain. Speculative demand determines, to some extent, rebar rolling schedules at mills and some inventories at fabrication shops. However, real demand controls rebar delivery to jobsites. The rebar subcontractor, as a customer of the structural engineer, may ‘pull’ rebar design from the engineer and thus, ‘drive’ the design of rebar configurations. However, project teams rarely include a rebar subcontractor during DD for a competitively bid project. Rather, the structural engineer completes rebar design such that any rebar subcontractor can bid on the work. Thus, the structural engineer cannot incorporate company-specific capabilities of the rebar subcontractor into the rebar design. Instead, once the owner hires the rebar subcontractor, structural engineers and rebar subcontractors rework the rebar design. New contractual and working relationships that treat rebar fabricators and placers as customers of the engineer could take advantage of their unique rebar knowledge and skills.

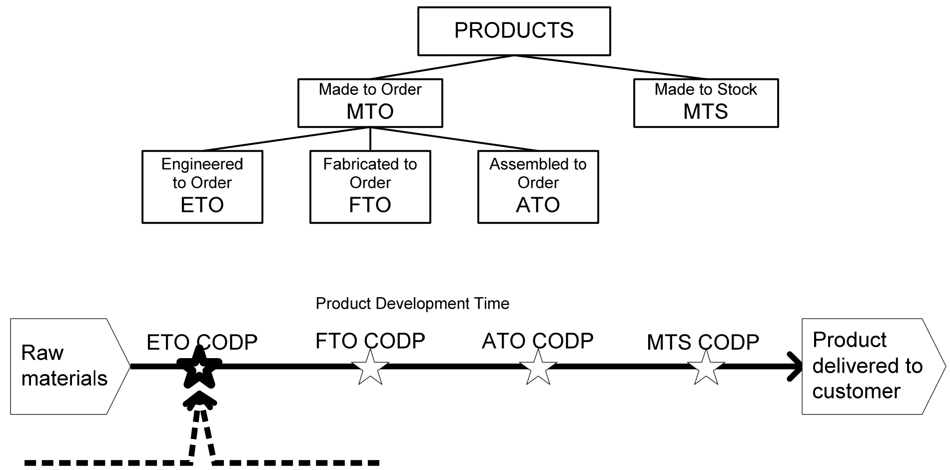


Figure 8. Types of products in relation to customer input (Figure 6.5 in Tommelein et al. 2009)

1.3.3 BUILDING INFORMATION MODELING (BIM)

This research examines design theory and methodology of an ETO product. Concurrently, it addresses tools available to support designers in collaborative design efforts. One such tool is BIM software.

Eastman et al. (2008, p. 13) define Building Information Modeling, or BIM, as "a modeling technology and associated set of processes to produce, communicate, and analyze building models." BIM, in some form, has been around since at least the 1970s (Eastman et al. 2008). BIM software products contain databases comprised of building components and material information. A 3D model is one output of these databases. BIM software can create a so-called 'virtual building' that allows project stakeholders to view clashes that may occur in their building systems, select construction methods suited to a given substructure based on the model, etc. The use of 3D BIM is becoming increasingly widespread in the AEC industry, as software and hardware costs no longer are major hurdles and as more owners and architects have experienced benefits and gain confidence in its use (Eastman et al. 2008; Fauerbach 2007; Goupil 2006).

BIM models not only reveal clashes between building components and building systems, but also within a single trade (Luth, personal communication, 10/1/06). Using BIM databases, designers can develop multiple design alternatives by changing single components, or systems, more quickly than if they had to detail each alternative separately. Further, BIM models provide a common language for design and construction teams, allowing them to *see* how the building fits together, although consistent use of naming conventions is still troubling industry developments (e.g., Industry Alliance for Interoperability). BIM models do not show tolerances by default; rather, design and construction teams need to account for these with design formalisms instead (e.g., modeling tolerance manually).

Designers can choose a level of detail when creating a BIM in keeping with the purpose their model is to serve. A model intended for determining basic construction sequencing does not need to be as detailed as one intended for detailing connections. A detailed BIM allows engineers to see rebar congestion. If rebar is too congested to fit as shown on the drawings or is too congested to pass inspection (as may be the case if the inspector feels there is not ample space for concrete between bars), the entire project schedule suffers because rebar installation precedes most other construction activities (e.g., concrete placing, piping, ductwork, etc.). Rebar may also fail field inspection as a result of poor quality placement (e.g., the bars are not plumb through column lifts). BIM cannot alleviate placing issues, but it can certainly bring congestion to the fore.

BIM tools allow designers to develop alternatives more quickly than design software without BIM databases. Developing alternatives supports set-based design; however, for BIM software to support set-based *rebar* design, it must include rebar configurations in its databases. Moreover, designers may find many feasible rebar configurations, and thus have many alternatives to model. BIM software that makes changing rebar configurations automatic, or at least straightforward, may be preferred over software that requires bar-by-bar detailing of each alternative. This dissertation explores the use of BIM tools to detail alternative rebar configurations. The author explored commercially-available BIM tools used in structural engineering and design offices, and selected two that warranted further study, AutoDesk Revit 2006 and Tekla Structures 12.0 (see Chapters 6 and 8).

BIM software products change rapidly, software companies release new versions approximately twice a year. When this research began, the AutoDesk Revit library did not include rebar: designers needed to create rebar objects in Revit and insert them into the model individually. This is no longer true: Revit 2009 now has a built-in rebar library. Table 1 shows the Two-List method of Choosing By Advantages (see Chapter 2, Section 2.4.2). It lists the advantages of AutoDesk Revit 2006 and Tekla Structures 12.0, in the author’s opinion, at the start of this dissertation research. It only compares software used by structural engineers, as the author had access to these, but not to 3D rebar detailing software widely used by rebar detailers, such as CADSUSA and RebarCAD. Table 1 does not compare structural analysis tools, e.g., SAP 2000, RISA-3D, etc., as the author’s scope did not require use of these tools.

Table 1. Comparison of reinforced concrete BIM capabilities

Advantages of AutoDesk Revit 2006	**Advantages of Tekla Structures 12.0**
Easier to generate a 3D rendering Easier to model concrete beams Easier to model concrete columns More widely used by designers (especially architects) in Northern California	Models bolts vs. does not model bolts Models rebar vs. not model rebar

1.3.4 PERFORMANCE-BASED REINFORCED CONCRETE DESIGN

In tandem with the development of new structural modeling software (e.g., BIM), structural design has seen the emergence of a performance-based design method that results in structures designed to meet certain owner-specified performance requirements. Moehle and Hamburger (2000, p. 6) explain the rise in demand for performance-based design:

> As a result of the [1989] Loma Prieta earthquake, many building owners and corporate tenants in older buildings began to become concerned that their buildings were not adequate to protect their financial interests in the event of future earthquakes [even though having met building code requirements at the time of construction]. These owners and tenants began to request that these buildings be upgraded. However, rather than asking that the buildings be upgraded to conform to the [most recent] building code, these owners and tenants began to ask engineers to design upgrades to meet very specific performance objectives related to the amount of business interruption and repair cost that may be incurred in a building for different levels of earthquake ground motion.

Performance-based design "seeks to improve seismic risk decision-making through assessment and design methods that have a strong scientific basis and that express options [alternatives] in terms that enable stakeholders to make informed decisions" (Moehle and Deierlein 2004). Performance-based design allows for building owners and structural engineers to choose amongst various levels of structural performance. Figure 9 shows the performance-based design process. Similar to set-based design, structural engineers design sets of alternatives in performance-based design and evaluate these sets based on performance criteria (referred to as ‘factors’ in CBA, see Section 2.4.1). ‘Select Performance Objectives’ (Figure 9) focuses on generating the factors used to evaluate the set of design alternatives. Design alternatives are generated in the ‘Perform Preliminary Design’ step. Performance capacities are verified, which corresponds to set narrowing, in the ‘Verify Performance Capability’ step. Performance-based design (Figure 9) incorporates the phases of the design process (Figure 3); however, it includes additional activities to focus the process on structural performance.

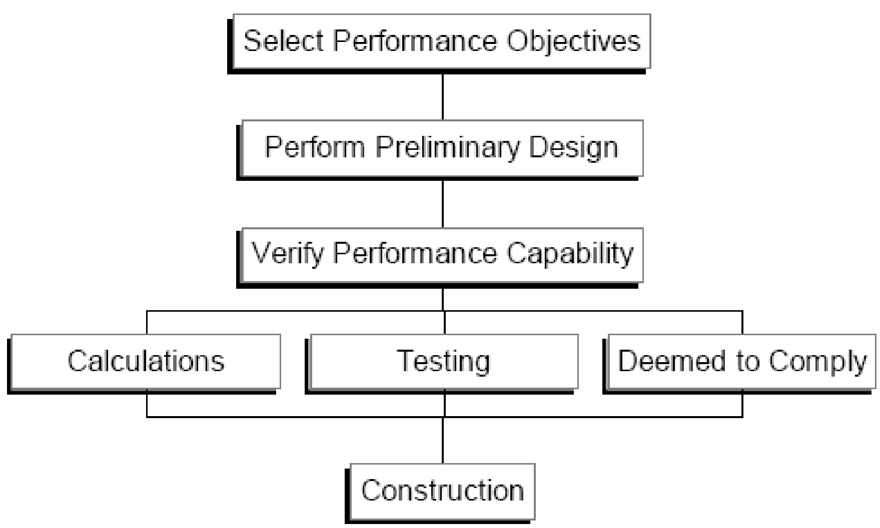


Figure 9. Performance-based design process (Figure 1 in Moehle and Hamburger 2000)

Rebar is an important attribute of the design alternatives generated in the performance-based design process, as rebar contributes to structural ductility and lateral force resistance, which translate into structural performance. Performance-based design and set-based design are similar in that both rely on involvement of many stakeholders to make satificing decisions, and both require that sets of alternatives be explored before committing to a final design. Performance-based design focuses on generating design alternatives that have different performance levels, selecting one, and proceeding with a point-based design process. Performance-based design evaluates design alternatives with a probabilistic assessment framework (Moehle and Deierlein 2004) which is beyond the scope of this dissertation. Set-based design focuses on generating design alternatives that provide value to the project as a whole and working with sets of alternatives throughout the design process. The author uses Choosing By Advantages (CBA) (see Section 2.4.2) to evaluate sets of design alternatives. A set-based methodology, combined with performance-based design, could be used to allow more alternatives to be explored and evaluated for performance.

1.4 RESEARCH OBJECTIVES

The objective of this research is to deliver a proof of concept that a set-based methodology can be used for rebar design. Specific research objectives include:

- To catalog structural design methodologies
- To document the use of set-based design on case-study projects.
- To gain an understanding of how the current BIM software may interface with a tool that supports a set-based methodology
- To illustrate an academic example of the rebar design process following a set-based methodology

1.5 SCOPE

This research focuses on the design phase of AEC projects and the stakeholders involved in design. This dissertation does not consider the construction phase in its entirety, but the author considers constructability concerns in design, including prefabrication decisions. Specifically, this research focuses on rebar design. Reinforced concrete design also includes mix design, formwork considerations, and possibly steel-concrete connections. However, the author does not explicitly consider these aspects in this work.

Due to the collaborative nature of a set-based methodology, this research assumes that an integrated project delivery (IPD) team (e.g., Matthews and Howell 2005) is being used. The Integrated Form of Agreement, developed by Lichtig (2005b), promotes collaboration among an IPD team and offers a method of risk sharing. Legal issues encountered in the implementation of a set-based methodology are outside the scope of this research. The author is delivering a proof of concept that a set-based methodology can be used for rebar design: whether or not this methodology is implemented in practice now or later falls out of the scope of this dissertation.

1.6 RESEARCH QUESTIONS

The following questions expand the body of knowledge about the design phase of AEC projects through action research (refer to section 1.7.2). Each of these questions applies to the application of set-based methodologies discussed in this dissertation.

Q1: Given the documented inefficiencies in the reinforced concrete product delivery system, are there opportunities for the application of a set-based methodology for the rebar design process?

Q2: What would a set-based rebar design process look like?

Q2.1: Who might be involved in set-based rebar design?

Q2.2: At what point in the design phase are set-based methods used?

Q2.3: What levels of detail define design alternatives?

Q2.4: What value tradeoffs are associated with the set of design alternatives?

Q2.5: How are sets of design alternatives narrowed?

Q2.6: How might stakeholders make design decisions in a set-based design environment?

1.7 RESEARCH METHODOLOGY

Case-study research and action research are used to develop the set-based methodology for rebar design. 'Proof of concept' experimentation expands the theoretical understanding of the design phase of AEC projects and expands the body of knowledge about rebar design. Case studies follow the application of set-based methods on two projects: (1) the expansion of the School of Cinematic Arts at the University of Southern California (USC) in Los Angeles, CA, and (2) the Cathedral Hill Hospital Project in downtown San Francisco, CA.

1.7.1 CASE-STUDY RESEARCH

Yin (1994) describes case-study research: "A case study is an empirical inquiry that investigates a contemporary phenomenon within its real life context, especially when the boundaries between phenomenon and context are not clearly evident." Case-study research is often criticized in the academic community (e.g., Meredith 1998; Schmenner and Swink 1998) because the results of case studies are not necessarily reproducible (Meredith 1998). Lack of reproducibility is a function of the inability to separate the phenomenon from its context and the inability to reproduce the researcher's perceptions of the case. Boundaries of case studies and the author's perceptions must be clearly documented to reduce confusion about the applicability of case-study findings.

Despite criticisms of case-study research, this methodology provides researchers with applicable findings. Meredith (1998) postulates case studies are useful for generating and extending theory, as case studies answer questions about “why?” rather than questions concerned with “what?” or “how?” that are more common in rationalist methods. Schmenner and Swink (1998) explain benefits of developing theories from real-world observations.

1.7.2 Action Research

Action research is rooted in social psychology. Historically, action research described situations where the researcher sought to bring about social change. In the context of this dissertation, the researcher advocated the change from a point-based design process to a set-based design process. Lewin (1947) first described action research as “a comparative research on the conditions of and effects of various forms of social action and research leading to social action.” Action research involves the researcher directly in the research project, often as a promoter of change (Susman and Evered 1978). The results of action research cannot necessarily be generalized for broad application, as action research seeks to find solutions that are “localized” for specific situations (Stringer 2007). Action research often occurs through case studies when new methodologies are being developed.

1.7.3 Workshops with Academic and Industry Participants

Workshops offer an opportunity for: (1) formulating research questions with industry input, (2) engaging industry in data collection, case-study identification, and testing of methodologies and tools, (3) receiving feedback from industry participants about the direction of the research, (4) disseminating research findings, and (5) soliciting ideas for other applications of the findings.

Throughout the course of this dissertation research, the research team hosted nine Rebar Workshops. Table 2 lists the workshop participants and which workshops they attended. Initially, workshops focused on explaining the concept of set-based design to workshop participants. At one workshop, the author presented a set-based methodology for designing longitudinal rebar in a shear wall. One participant explained to her that longitudinal rebar rarely adds much difficulty to rebar placement in a shear wall; in fact, the transverse rebar is the more challenging part of the placement. Exchanges such as these shaped the author's research direction, and allowed her to better understand the industrial value of her research. At later workshops, participants presented status reports about set-based design in pilot projects, their values as project stakeholders, and data trends from their industry. In the final workshop, they participated in Analytic Hierarchy Process (AHP) and Choosing By Advantages (CBA) exercises (presented in Chapter 8).

1.7.4 USE OF MODELING FORMALISMS AND TOOLS

In order to determine where this research 'fit' in the industry, the author modeled the current rebar design and delivery system with a cross-functional diagram to understand what activities would be impacted by a change from point-based design to set-based design. She transformed the cross-functional diagram into a design structure matrix (DSM) to reveal opportunities for implementation of set-based design. She explored the use of BIM software to aid in the implementation of set-based design.

Table 2. Workshop participants and attendance

Participant	Affiliation	Project Role	Workshop I 8/17/06	II 10/13/06	III 12/15/06	IV 4/16/07	V 9/7/07	VI 12/7/07	VII 4/11/08	VIII 9/19/08	IX 2/13/09
Greg Angstadt	GJH Rebar Services, Inc.	Fabricator			X						
Ashkan Arhami	UC Berkeley	Undergraduate Student									X
Glenn Ballard	UC Berkeley	Professor & co-PI	X	X	X	X	X	X	X	X	
Michelle Bennette	Nibbi Concrete	General Contractor							X		
Howard W. Bennion	Pacific Coast Steel, Inc.	Fabricator		X		X	X	X		X	
Paul Chambers	Capital Project Management	Construction Manager				X					
Caroline Clevenger	Stanford University	PhD Student					X				
Julia Davis	UC Berkeley	MS Student					X				
Luis DelRosario	TAMCO Steel, Inc.	Steel Mill								X	
Jim Dick	Pankow Builders	Design Builder					X	X			
Andy Dickey	Tekla, Inc.	Software							X		
Kristen Erickson	Gregory P. Luth and Associates	Structural Engineer									X
Jim Fullerton	CRSI	Industry Association					X	X	X	X	
John Haymaker	Stanford University	Professor					X				
David Horton	CMC Rebar	Fabricator			X						
Stanley Johnson	Erico, Inc.	Supplies			X						
Joshua Kardon	Joshua B. Kardon + Company	Structural Engineer	X	X	X	X	X	X	X	X	X
Gregory Luth	Gregory P. Luth & Associates, Inc.	Structural Engineer	X	X		X		X			
Carlos Machado	Gregory P. Luth & Associates, Inc.	Structural Engineer							X		
David Mar	Tipping Mar + associates	Structural Engineer			X						
Andrew Marlen	TAMCO Steel, Inc.	Steel Mill								X	
Thomas McShane	CRSI	Industry Association		X	X		X				
Jack Moehle	UC Berkeley	Professor & co-PI	X								
Simin Nasseh	Forell/Elsesser Engineers	Structural Engineer					X				
John Oliva	Gregory P. Luth and Associates	Structural Engineer					X				
Layne Olson	Harris Rebar	Detailer									X
Kristen Parrish	UC Berkeley	PhD Student & Researcher	X	X	X	X	X	X	X	X	X
Luis Perez	Pankow Builders	General Contractor								X	
Chris Plue	Webcor Concrete	General Contractor	X								
Holly Razzano	Degenkolb Engineers	Structural Engineer		X	X						
Tim Schrotenboer	Gregory P. Luth & Associates, Inc.	Structural Engineer							X	X	
Kawai Sham	UC Berkeley	Undergraduate Student									X
Mike Sherritt	Ironworkers Local Union 416	Union Hall		X	X		X	X	X		
Lyle Sieg	Harris Rebar	Fabricator		X							
Carol Soares	UC Berkeley	MS Student								X	
Sandy Soulé	Soulé Software	Software			X	X	X	X	X	X	X
Jim Soule	Harris Rebar	Fabricator	X	X		X	X	X			
Boza Stojadinovic	UC Berkeley	Professor & co-PI	X	X	X	X	X	X	X	X	
Wendy Taniwangsa	Gregory P. Luth and Associates	Structural Engineer					X				
Iris Tommelein	UC Berkeley	Professor & PI	X	X	X	X	X	X	X	X	X
Stanislaus Tuholski	Lawrence Livermore Nat'l. Lab./UC Berkeley	Owner & PhD Student	X	X	X						
Bethany Walker	CRSI	Industry Association					X		X		X
John-Michael Wong	UC Berkeley	PhD Student & Researcher	X	X	X	X	X	X	X	X	
You Dajiang (John) Ying	Beijing Motorized Construction Co., Ltd.	Vice-General Manager									X
Cheng Ying	UC Berkeley	Visiting Scholar									X

1.8 DISSERTATION STRUCTURE

Chapter 2 of this dissertation reviews literature relevant to design theory and methodology (including set-based design), decision-making in design (including a comparison and selection of decision-making systems), and design evaluation and management tools. It highlights contributions from new product development, lean production philosophy, and structural design methodologies.

Chapter 3 presents the current state of design theory and methodology in the domain of structural engineering. This characterization of the current state is based on responses to a questionnaire sent to faculty and practitioners in the San Francisco Bay Area. The findings from this questionnaire help frame the case-study findings.

Chapter 4 illustrates the methodology for transforming a cross-functional diagram into a design structure matrix, or DSM. Both cross-functional diagrams and DSMs show iteration in a process. However, A DSM makes iteration more visually apparent. Analysis of a DSM may reveal opportunities for application of set-based design.

Chapter 5 shows, through example, the Choosing By Advantages (CBA) decision-making system applied to a rebar design problem. This chapter highlights the vocabulary and principles central to CBA. The CBA process is illustrated through design of a beam-column joint.

This research examines two case studies to understand what “works” in rebar design and construction in the context of actual projects. Local Bay Area firms let the author study and document projects using a set-based methodology for design. Following the progress of these projects gave the author insight about the successes and the challenges of rebar design and the application of set-based methodologies to this process. The set-based methodology developed herein incorporates concepts that led to successful projects, such as integrated project teams, early collaboration, and others.

Chapter 6 presents the USC School of Cinematic Arts Complex Expansion project. The structural engineer on this project implemented set-based methods to design the prefabricated rebar cages and to offer a choice of corner details for walls. This chapter documents the constraints used in developing the prefabricated panels. Further, this chapter synthesizes the reactions of the structural engineer, project foreman, and rebar placer to set-based design process. Finally, this chapter documents how the structural engineer used Tekla Structures (versions 12.0, 12.1, 13.0, and 13.1) on this project.

Chapter 7 presents the Cathedral Hill Hospital (CHH) project. The CHH project team has rigorously been implementing set-based design methods. This case study illustrates how sets of design alternatives may be generated and defined. This chapter also documents the use of A3 reports and CBA on the CHH project.

Chapter 8 presents an academic example of set-based rebar design of a shear wall. This example synthesizes the learning from the case studies and the literature review and showcases the methodology for designing this rebar. This chapter also presents a software tool developed by the author and her colleague Dr. John-Michael Wong, SetPlan, that works with Tekla Structures 14.0 to aid in set-based design.

In closing, Chapter 9 presents conclusions drawn from the case studies and the academic example. This chapter discusses the contributions to knowledge and suggests possible future research in the areas of set-based design and design decision-making.

CHAPTER 2. LITERATURE REVIEW

This literature review serves three purposes: (1) to understand the current state of knowledge both in industry and in academe, (2) to provide a vocabulary for this research that is consistent with previous and current research in the field, and (3) to understand the context for the original contribution of the author's work.

2.1 DESIGN THEORY AND METHODOLOGY (DTM)

Section 1.4.1 presented the need for and value of having design theory. Researchers may be able to extract design theory from design methodologies to develop design theory and methodology (DTM). Cross (2008, pp. 46-47) explains design methods:

> Design methods can, therefore, be any procedures, techniques, aids, or 'tools' for designing. They represent a number of distinct kinds of activities that the designer might use and combine into an overall design process. Although some design methods can be the conventional, normal procedures of design, such as drawing, there has been a substantial growth in new, unconventional procedures that are more usually grouped together under the name of 'design methods.'
>
> The main intention of these new methods is that they attempt to bring rational procedures into the design process. It sometimes seems that some of these new methods can become *over*-formalized, or can be merely fancy names for old, commonsense techniques. They can also appear to be *too* systematic to be useful in the rather messy and often hurried world of the design office. For these kinds of reasons, many designers are still mistrustful of the whole idea of 'design methods.'
>
> The counterarguments to that view are based on the reasons for adopting systematic procedures… For instance, many modern design projects are too complex to be resolved satisfactorily by the old, conventional methods. There are also too many errors made with the conventional ways of working, and they are not very useful where team work is necessary. Design methods try to overcome these kinds of problems, and, above all, they try to ensure that a better product results from the new design process. They can also be good practice methods for student designers, offering a training in certain ways of thinking and proceeding in design…

> The new methods tend to have two principal features in common. One is that they *formalize* certain procedures of design, and the other is that they *externalize* design thinking. Formalization is a common feature of design methods because they attempt to avoid the occurrence of oversights, of overlooked factors in the design problem, of the kinds of errors that occur with informal methods. The process of formalizing a procedure also tends to widen the approach that is taken to a design problem and to widen the search for appropriate solutions; it encourages and enables you to think beyond the first solution that comes into your head.

Research at the Project Production System Laboratory (P^2SL) at the University of California, Berkeley focuses, in part, on the development of formal DTMs and the application on temporary project production systems (including structural engineering design) within the AEC sector. Set-based design strategies (Parrish et al. 2008a), the design structure matrix (DSM) (Tuholski 2008; Tuholski and Tommelein 2009a), and multiple domain matrices (MDM) (Maurer 2007; Tuholski 2008) show promise as DTMs that drive design process improvements and the exploration of project delivery theory. Researchers may categorize these DTMs as prescriptive methodologies; they embody or enable characteristics that a design process *ought* to have. Little literature, however, is available on DTM research and development in the context of structural engineering design on AEC projects. This lack of literature may be attributed to the lack of theory of project management (Koskela and Howell 2002; Koskela et al. 2002).

The predominant emergent DTM addressing design and construction is the Transformation-Flow-Value (TFV) theory of production (Koskela 1992; 2000; Koskela and Howell 2002). This theory, elaborated on later in this chapter, serves as the backbone of the growing 'lean movement' within the AEC sector. Koskela proposes TFV theory as a means of describing, understanding, and teaching AEC design and construction (production system) behaviors.

2.1.1 CANONICAL STRUCTURAL ENGINEERING DESIGN THEORY METHODOLOGIES (SE DTMS)

Academic development of DTMs within the structural engineering community has been limited. Few design texts describe formal DTMs. Those that do present point-to-point solution or optimization algorithms (Parrish et al. 2007). The typical structural engineering approach proceeds with the following steps (Stephenson and Callander 1974, p. 3):

a) Statement of the problem.

b) Collection of relevant data.

c) Consideration of possible courses of action.

d) Selection of preferred solution.

e) Detailed development of design.

f) Construction of prototype, development work.

g) Production.

"Two approaches to stages (c) and (d) are suggested. In the first, referred to as the 'cut and try' approach, a designer can use experience or history to assume a solution and then analyze it. In the second, referred to as 'synthesis' approach, the designer builds up a solution from "a collection of decomposed and optimized parts" (Stephenson and Callander 1974, p. 7). This 'point-to-point' methodology is quite similar to the canonical mechanical engineering DTM approach (Peters and Hopkins 1996; Ward et al. 1995), and has remained the status quo for decades.

Alternative methods of design have been developed by architectural schools of design, however, most are artistic in nature and as such they are beyond the scope of this dissertation. Architects have begun to develop integrated methods of design in conjunction with structural engineers. Lin and Stotesbury (1981) were among the first to describe complete building design integration from an engineering perspective. They described the design process as (ibid, p. 3):

> Architectural design is a complex spatial orientation problem. The designer must organize the performance properties of buildings to fill a broad range of user needs. The performance properties include:
>
> 1. Activity-Associated (operational)
> 2. Physical (constructive)
> 3. Symbolic (experimental)

The successors of this facility integration concept fall under the umbrellas of green design, lifecycle analysis, and also lean construction. They consider the integration of architecture and engineering in support of overall building systems goals. The structural engineering community provides few additional formal DTM methods or applications regarding activity sequencing, work structuring, or value management.

2.1.1.1 Structural Engineering DTMs in Education

At the basic level, structural engineers are responsible for selecting a configuration of material to resist a set of applied loads. This is not a trivial task—understanding design loads and developing a scheme to resist these loads is both a creative and technical process. Introductory courses in structural engineering design often include a course in steel design, a course in reinforced concrete design, and possibly a course in another material (e.g., timber). The methods taught in design classes often use 'trial and adjustment' processes. These characterizations support a point-based design methodology

(Ward et al. 1995), where an initial design (or point) is selected and then refined through iteration until a feasible solution is developed.

The point-based approach aids solutions developed by the structural engineering community in two ways: (1) it imposes linearity on otherwise non-linear systems through prescribed procedures and standardized assumptions and, (2) it initiates trial solutions based on rules-of-thumb and assumptions formalized through testing, theoretical development, or historical record, thereby increasing the iteration gradient of recurring linear trials. Tuholski (2008, pp. 50-51) explains, “in this context, iteration gradient refers to the slope of the line formed by plotting the number of iterations against the difference between successive solutions. Structural engineers tend to focus on optimizing solutions in the context of their requirements, with less regard for system-wide performance.” As the structural engineer is contractually required to develop a ‘single’ solution, they may not have an incentive to explore options that optimize the system as a whole.

MacGregor and Wight’s (2005, p. 12) introductory reinforced concrete design textbook describes design as “a sequential and iterative decision-making process.” Similarly, Nawy (2000, p. 4) explains:

> A trial section has to be chosen for each critical location in a structural system. The trial section has to be analyzed to determine if its nominal resisting strength is adequate to carry the applied factored load. Since more than one trial is often necessary to arrive at the required section, the first design input step generates a series of trial-and-adjustment analyses.

MacGregor and Wight (2005, pp. 13-14) define three basic limit states, or points when a “structure or structural element becomes unfit for its intended use… (1) Ultimate limit states—involving structural collapse of all or part of a structure, (2) Serviceability limit states—involving disruption of the functional use of the structure, and (3) Special limit states—involves damage or failure due to abnormal conditions or loadings.”

Reinforced concrete design tries to avoid these limit states. To do so, designers specify structural elements that are stronger than the expected loadings. However, because of uncertainty in loadings and structural capacities, they also use safety factors. Engineers calculate safety factors to minimize the probability of failure of a given member. Based on experimental testing, engineers calculate safety factors that limit the probability of failure to 1/999 (MacGregor and Wight 2005, p. 20). Safety factors also impose linearity on the design process by eliminating the need to explicitly calculate concrete behavior. Safety factors are used to make the behavior more 'predictable' and the design process that much easier.

Design texts often begin with assumptions in order to simplify the design process. For instance, ACI 318 adopts a capacity design approach, which "controls" failure by over-designing elements relative to the one planned to "fail." This first assumption allows the designer a place to start when, e.g., designing a shear wall for lateral loads—the plastic hinges are assumed to form, and remain elastic in shear, at the base of the wall (MacGregor and Wight 2005, pp. 950-951). Designers may use an inverted triangular load pattern to represent earthquake loading. Although earthquake loads are dynamic, the design procedure is simplified if these loads are assumed to be static. Structural engineers apply a strength reduction factor, ϕ (a safety factor) to member strengths to effectively amplify the static loads, by reducing the strength of the concrete members. The ϕ factor is determined theoretically and verified by experiment (ACI 2005). Assumptions about material behavior also make the design process more linear than it would otherwise be. That is, assumptions allow designers to complete a design, check it, and then adjust, rather than test materials at the project outset to determine their properties. Section 9.3.2

of ACI 318 lists values for ϕ depending on load conditions and uncertainties about member strength.

Similarly, in steel design, textbook methods (Salmon and Johnson 1996, p. 752) simplify equations by first categorizing behaviors, "Because of the failure modes, no simple design procedure is likely to account for such varied behavior. Design procedures generally fall in one of three categories: (1) limitation on combined stress, (2) semi-empirical interaction formulas, based on working stress procedures, and (3) semi-empirical interaction procedures based on strength." These three types of procedure are commonly applied to six common classifications of failure. The purpose of providing general procedures as applied to dominant failure modes is to simplify, or 'impose linearity', on otherwise complex behaviors. In the same way, the higher-order effects of secondary bending are simplified with approximate linear solutions. These approximations are justified by theoretical derivation (Salmon and Johnson 1996, pp. 757-758).

Structural engineers also use assumptions to initiate solutions and increase the iteration gradient in steel design. Experimental testing shows simplified assumptions regarding the effective length, labeled KL, of compression members to be theoretically conservative (Salmon and Johnson 1996, p. 757). The American Institute of Steel Construction (AISC) presents suggested constants, C_m, governing moment magnitude (secondary flexural effects) in tabular form (Salmon and Johnson 1996, p. 759). These constants are theoretically derived and verified experimentally. Additional rules-of-thumb have been developed by AISC and are shown in design texts. These rules guide the first 'guess' for steel sections based on applied loadings and offer reasonable assumptions for flange width-to-thickness ratios to be verified upon solution completion. Finally, design tables for beam and column selection are presented in AISC (1990) for use in the repeated trial with subsequent verification.

Structural design education strongly emphasizes the analytical elements of design. The more creative part of the process (e.g., developing innovative solutions not found in tables, collaborating with other designers), is not emphasized in college-level structural engineering courses. By contrast, these creative skills are the focus of courses taught in architecture, mechanical engineering, or in business departments.

2.1.2 DTM IN NEW PRODUCT DEVELOPMENT AND MECHANICAL ENGINEERING

Researchers historically have explored DTMs through the study of manufacturing and new product development. An extensive body of literature is available on classification systems and summary descriptions of DTM research (e.g., Cross 2008; Finger and Dixon 1989a; 1989b; Krishnan and Ulrich 2001; Waldron and Waldron 1996; Wynn and Clarkson 2005). Table 3presents a research summary of DTMs. The references presented in this table establish a point of departure for the future application of DTMs within structural engineering design.

2.1.2.1 Process View of DTM

The process view on design methodologies looks at *how* teams and individuals perform design activities. Waldron and Waldron (1996) explain, “The design process can be viewed as a sequence of steps, such as clarification of the specifications and the environment in which the design will function, understanding the behavior, and establishing the operational constraints, including manufacture, servicing, marketability, usability, and disposability.” Literature presenting the process view of design is subdivided into theoretical, experimental, and review of methods. The theoretical literature postulates how and why design processes evolve. The experimental literature explores DTM based on observed behaviors. The “Review of Methods” (Table 3) lists literature reviews published by other researchers.

Table 3. Design Theory and Methodology Taxonomy

View	Description	References
Process View of Design	Theoretical	(Costa and Sobek II 2003) (Ford and Sobek II 2005) (Gil et al. 2005) (Ward 1990) (Hubka and Eder 1996) (Cross 2008) (Pahl et al. 2007) (Ward et al. 1995)
	Experimental	(Whitney 1990) (Jain and Sobek II 2006) (Tang and Leifer 1991) (Spear and Bowen 1999) (Jin and Levitt 1996)
	Review of Methods	(Finger and Dixon 1989b) (Finger and Dixon 1989a) (Peters and Hopkins 1996) (Waldron and Waldron 1996) (Krishnan and Ulrich 2001)
Artifact View of Design	Theoretical	(Albano and Suh 1992) (Aganovic et al. 2004) (Srinivasan et al. 1997) (Waldron and Waldron 1996) (Ulrich and Eppinger 2004) (Clausing 1994)

From a process viewpoint, design is classified as descriptive or prescriptive. Descriptive processes, on the one hand, describe the sequence of activities typically performed in design and tend to emphasize the importance of generating a solution concept early (Cross 2008). Prescriptive models, on the other hand, offer a more systematic procedure to follow (i.e., what the design process *should* look like) and tend to emphasize the importance of fully understanding the problem(s) before generating solution concepts (Cross 2008).

2.1.2.2 Artifact View of DTM

Researchers also describe DTMs from the artifact view, which characterizes DTMs based on the artifacts they yield.

Waldron and Waldron (1996) contrast the artifact view of design with the process view of design, saying “the design process may be viewed as creating conceptual design for the artifact, testing and evaluating the designed artifact, and, based on the results, refining and optimizing the design, until some satisfying criteria is reached.” Publications on the artifact view of design tend to be theoretical in nature. However, in practice, most design is artifact focused. This discrepancy highlights the lack of literature describing the current DTMs in use.

2.2 TRANSFORMATION FLOW VALUE THEORY AND LEAN DESIGN

The emergent AEC DTM theory is associated closely with the ‘lean movement.’ Lean design and construction integrates three competing management views: (1) transformation, (2) flow, and (3) value generation (TFV) (Howell and Koskela 2000; Koskela 1992; Koskela 2000). In the transformation view, “production is conceptualized as a transformation of inputs to outputs” (Koskela et al. 2002). Conventional construction is predominantly managed in accordance with the transformation view while ignoring flow and value generation, e.g., management efforts are centered on individual task optimization and resource productivity (Koskela 1992). The transformation view has two deficiencies (Koskela et al. 2002): “It is not especially helpful in figuring out (1) how to avoid wasting resources, and (2) how to ensure that customer requirements are met in the best possible manner.”

Projects managed using such conventional approaches tend to be ineffective and inefficient (Koskela and Vrijhoef 2000). In the flow view, goals include reducing variation, clearly articulating and simplifying handoffs, and decreasing lead times. In the value view, goals include identifying customers at all levels and generating value for all.

"The crucial contribution of the TFV theory of production lies in calling attention to modeling, structuring, controlling, and improving production from these three points of view combined" (Koskela et al. 2002). Project participants who are missing opportunities to generate value and tolerating waste (Ballard 2000b; Koskela 2004; Ohno 1988) will benefit from innovative design methodologies to improve their practices.

Project managers may gain insight into processes by considering the transformation, the flow, and the value view. Similarly, they may gain insight into processes by considering multiple stakeholder views and integrating them.

2.3 MULTIPLE OBJECTIVE OPTIMIZATION

Ward (2007) explains the need for multiple objective optimization and knowledge capture for successful implementation of a set-based methodology. Limited literature is available on multiple objective optimization in the AEC industry. However, the literature found explains the concepts of knowledge capture and value trade-offs in support of satisficing multiple stakeholders.

Researchers use optimization methods to make decisions amongst design alternatives. Panchal et al. (2008) describe one such method. Their paper describes the trade-off between the accuracy of a simulation model and the cost of further developing that model. This trade-off is similar to one faced in rebar design: deciding how much detail is necessary to progress with design, compared to the restrictions imposed by selecting a rebar configuration, before the rebar fabricator and placer can give input. For instance, the decision to use concrete shear walls may require that the shear walls be sized before progressing with design. This decision does not, in and of itself, require that rebar configurations be selected. However, the structural engineer may opt to detail the rebar immediately to determine the feasibility of given shear wall dimensions. Panchal et al. (2008) suggest the use of a value-of-information approach that (1) quantifies the added value of gaining more information into an information potential metric and (2) uses this metric to support model refinement for making decisions about model development.

Ward (2007) and Xu et al. (2006) apply multiple objective optimization. Knowledge capture and reuse is a fundamental concept in the development and use of value propositions. Ward (2007) illustrates the importance thereof for the purpose of making the product and process development cycles more efficient. Xu et al. (2006) describe the benefits of knowledge reuse as well as a method for capturing this knowledge, and they explain the need for synthesizing the knowledge of previous projects into the new product development process. Xu et al. (2006) introduce a method of cataloging product designs based on their functions and key characteristics. This catalog can then be searched and knowledge can be extracted for use in future product development cycles. Knowledge capture is also important in a set-based methodology for rebar design as knowledge from one project can be used on future projects if it is stored.

Set-based design requires satisficing multiple stakeholders. Understanding each stakeholder's values is a necessary first step in satisficing them. When stakeholders understand each other's values, they can make decisions in light of these values. Thus, they need a group decision-making process that accounts for different stakeholder values.

2.4 DECISION-MAKING PROCESSES

Decision-making is at the heart of set-based design. Design teams use decision-making skills to design the initial set of alternatives, to determine who to include in decision-making at a given stage of the design process and to determine the importance of advantages of each alternative (see section 2.3.2).

Set-based design requires groups of stakeholders to make decisions, so the author explored decision-making systems tailored for group use before selecting systems to review in depth. Table 4 compares the decision-making systems considered. Saaty (1990) developed the Analytic Hierarchy Process (AHP) that makes use of pair-wise comparisons in decision-making. Suhr (1999) developed the Choosing By Advantages Decisionmaking System (CBA) that considers advantages of alternatives and makes comparisons based on these advantages. Thurston (1990; 2006) explains Multi-attribute Utility Theory in the context of engineering decision-making that involves assigning preference to multiple attributes and combining these preferences (via weighted averages) to determine the most preferred one. Ullman (2001) explains Robust Decision-making that focuses on making decisions given incomplete information.

Table 4 shows the author's assessment of these decision-making systems. She assesses how they support group decision-making to determine the system's fitness for set-based design. Set-based design may involve sharing incomplete information (e.g., the structural engineer provides a range of beam dimensions rather than specific beam dimensions); the author assesses whether or not each system supports this type of information in the 'Support incomplete information' factor. The 'Clear vocabulary' factor answers the question, "Will (relatively) novice system users understand the distinction between different words in the system?" The factor 'Easy to use' shows the author's assessment of the system's level of difficulty. She made this assessment primarily based on the math skills required to use the system. The factor 'Generates alternatives' assesses whether or not the system promotes developing new alternatives. The factor ‘High level of abstraction’ compares whether or not a system directly compares alternatives or if they require users make extrapolations to compare them. The factor ‘Commercially used’ compares whether or not literature reports use of the system in industry. The factor ‘Software package’ compares whether or not a computer software package exists specifically for the decision-making system.

Table 4. Comparison of decision-making methods

Factors	Analytic Hierarchy Process	Choosing By Advantages	Multi-attribute Utility Theory	Robust Decision-Making
Designed for group decision-making	Yes	Yes	No	Yes
Support incomplete information	No	Yes	Yes	Yes
Clear vocabulary	Yes	Yes	Yes	Yes
Easy to use	No	Yes	No	Yes
Generates alternatives	Yes	Yes	Yes	Yes
High level of abstraction	No	No	Yes	No
Commercially used	Yes	Yes	Yes	No
Software package	Yes	No	No	Yes

Based on the comparison in Table 4, two decision-making processes were reviewed in detail, AHP and CBA. The author eliminated Multi-attribute utility theory because it is not intended for group decision-making. She did not consider Robust Decision-Making because she discovered it after she had already began exploring AHP and CBA. However, the system bears further study, so she included it in Table 4. Each of these methods is designed to be used for group decision-making, focus on generating alternatives, and both are, to some extent, used commercially. AHP is widely used commercially (Robust Decisions Inc. 2008), and CBA incorporated most of the factors on the “wish list” for a set-based design decision-making method, so these were reviewed for use in the set-based design process.

2.4.1 ANALYTIC HIERARCHY PROCESS (AHP)

Saaty (1990) defines the Analytic Hierarchy Process (AHP) as "a multi-criteria decision making approach in which factors are arranged in a hierarchic structure."

2.4.1.1 Description of AHP

AHP provides a means of making a rational decision while attempting to satisfy multiple criteria. The system uses matrix algebra to rank and eventually select one of *x* alternatives. Decision-makers sort criteria into a hierarchy that compares criteria of similar granularity. That is, items "must be compared in sets of objects of their class" (Saaty 1990, p. 9). This allows the pair-wise comparison of criteria. Once sorted by granularity, decision-makers compare pairs of criteria and develop a matrix, A, that lists relative weights of the various criteria, where $a_{ij} = w_i / w_j$ is the *relative weight of criteria i with respect to criteria j*.

Table 5 shows the Fundamental Scale decision-makers use to determine weights (Saaty 1990). Note that A satisfies the reciprocal property, i.e., $a_{ij} = 1/a_{ji}$. Figure 10 shows a three-level hierarchy comparing three alternatives (Alternatives A, B, and C) according to five criteria (Criteria 1, 2, 3, 4, and 5). Equation 1 shows the corresponding relative weight matrix, A, for this hierarchy.

Table 5. Fundamental Scale (Table 1 in Saaty and Vargas 1994)

Intensity of Importance on an Absolute Scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed

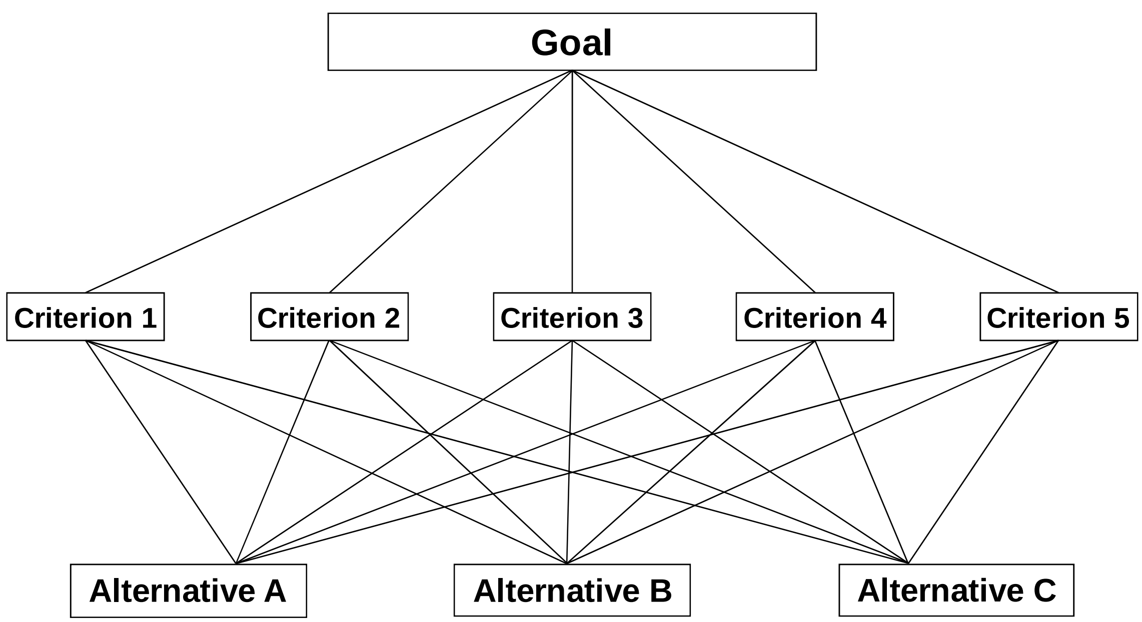


Figure 10. Three-level hierarchy

$$A = \begin{pmatrix} {}^{w_1}/_{w_1} & {}^{w_1}/_{w_2} & \cdots & {}^{w_1}/_{w_5} \\ {}^{w_2}/_{w_1} & {}^{w_2}/_{w_2} & \cdots & {}^{w_2}/_{w_5} \\ \vdots & \vdots & \ddots & \vdots \\ {}^{w_5}/_{w_1} & {}^{w_5}/_{w_2} & \cdots & {}^{w_5}/_{w_5} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{15} \\ a_{21} & a_{22} & \cdots & a_{25} \\ \vdots & \vdots & \ddots & \vdots \\ a_{51} & a_{52} & \cdots & a_{55} \end{pmatrix}$$

$$where\ a_{ij} = \frac{weight\ of\ criterion\ i}{weight\ of\ criterion\ j} = relative\ weight\ of\ criterion\ i\ with\ respect\ to\ criterion\ j$$

Equation 1. Relative weight matrix for the three-level hierarchy

The eigenvector of the relative weight matrix, A, called the priority vector, represents the relative importance of a given criterion.

Local weights compare the ability of each of *x* alternatives to meet each of *n* criteria at a given level. In the three-level hierarchy presented, for example, the decision-makers would develop five (*n*) individual 3 x 3 (*x* x *x*) matrices to determine these local weights. Each element in these matrices compares the ability of each alternative to meet a given criterion (i.e., how well does Alternative A meet Criterion 1 compared to the ability of Alternative B to meet Criterion 1?). Table 6 shows one local weight matrix. It compares the ability of Alternatives A, B, and C to meet Criterion 1. The 6 in the second column of the first row denotes that the decision-makers consider Alternative A to be 6 times better than Alternative B with respect to Criteria 1. Similarly, the 4 in the third column of the second row denotes that the decision-makers consider Alternative B to be four times better than Alternative C with respect to Criterion 1. The entries below the diagonal illustrate the reciprocal nature of the matrix.

Table 6. Sample local weight matrix

Criterion 1	A	B	C
A	1	6	8
B	1/6	1	4
C	1/8	1/4	1

An eigenvector is computed for each of the five matrices, leading to a set of five local weight vectors. Decision-makers sum the product of each alternative's local weight and that criterion's local priority to calculate the score of a given alternative.

Note decision-makers may create a multiple-level hierarchy (e.g., one or more levels of *n* sub-criteria), thus leading to multiple levels of "local weights." The procedure repeats for each level of the hierarchy; first determine the priority vector for the criteria, then develop local weight matrices for each of the *n* criteria at a given level of the hierarchy.

The alternative with the largest global priority is the "best" decision according to AHP. Note this alternative may not have the largest local weight with respect to each of the criteria. AHP is perhaps best explained through example (see 2.4.1.2). Saaty (1990) and Shtub et al. (2005) also provide examples.

2.4.1.2 AHP Example: Selecting a Rebar Terminator

This fictitious example illustrates how decision-makers may use AHP to decide how to terminate rebar entering a beam-column joint. The end of a piece of rebar cannot carry any load. In fact, rebar develops strength over its length. Thus, engineers need to allow rebar 'to develop' (gain strength) or upon loading the rebar will get pulled out of the concrete matrix surrounding it. In some cases, sufficient development length does not exist in a beam-column joint. So, engineers may try to hook bars into the joint to develop strength (Figure 11), or use T-heads, mechanical devices attached to the end of rebar that provide strength. Figure 12 shows a T-head. Structural engineers may specify T-heads in areas of extreme congestion (T-heads help reduce congestion by eliminating the need for a hooked end of a bar).

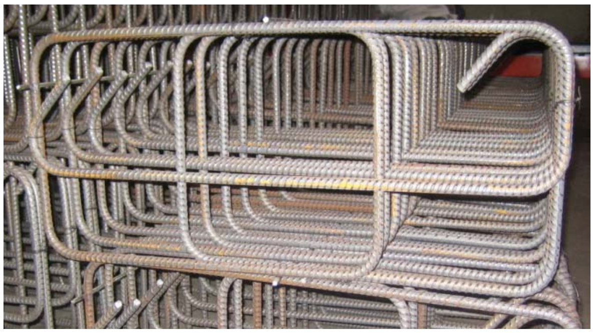


Figure 11. Hooked rebar (photograph taken by Kristen Parrish, 12/01/06)

Figure 12. T-headed rebar (photograph from www.hrc-usa.com)

The city of San Francisco, CA hires the structural engineering firm A+ Engineers, located in Oakland, CA, to provide structural engineering services for their new office building, located at the corner of Fourth Street and Brannan Street in downtown San Francisco. A+ Engineers and the architect, BrownGroup, decide to use a 4,000 psi concrete shear wall to resist earthquake loading. A+ Engineers details rebar in the wall, and decides to reinforce the shear wall's coupling beams with grade 60 #7 bars. ACI 318 (2005), Section 12.2.2, defines development length, l_d:

$$l_d = \left\{\frac{f_y \Psi_t \Psi_e \lambda}{20\sqrt{f'_c}}\right\} d_b = 41.5\ in$$

where	f_y	= yield stress of rebar	= 60,000 psi
	f'_c	= compressive strength of concrete	= 4,000 psi
	Ψ_t	= traditional reinforcement location factor	= 1.0
	Ψ_e	= coating factor	= 1.0
	λ	= concrete weight factor	= 1.0
	d_b	= diameter of rebar	= .875 in

Equation 2. Development length calculation (ACI 2005)

BrownGroup and A+ Engineers design the boundary elements of the shear wall to be 40 in. deep, thereby requiring T-heads or hooks at the end of the coupling beam rebar. A+ Engineers specify ‘HRC T-heads or equal’ on their structural drawings. They have successfully used these T-heads on three past projects and know the people at HRC. HRC does not sell T-heads individually; rather, they install T-heads at their shop, located in Fountain Valley, CA. The owner includes these drawings in the bid package sent to subcontractors.

Fabricator-placers A, B, and C all bid on the office building project. Fabricator A, located in Fairfield, CA, has a fabrication shop that installs Lenton T-heads, though not HRC T-heads. Fabricator B, located in Livermore, CA, does not have in-house capacity to install T-heads and neither does Fabricator C, located in Etiwanda, CA.

In part reflecting their physical location relative to the project site, and different fabrication capabilities, Fabricators A, B, and C each provide different details when they bid for the job. Fabricator A suggests using an alternative T-head. Fabricator B suggests using hooks, rather than T-heads, to develop bar strength. Fabricator C bids the work with HRC T-heads.

A+ Engineers review each of the bids to help the owner choose a sub-contractor. They use ACI 318 (2005), Section 12.5.2, to determine the development length for the hooks Fabricator B suggests:

$$l_{dh} = \left(\frac{.02\Psi_e \lambda f_y}{\sqrt{f'_c}}\right) d_b = 16.6\ in$$

where	f_y	= yield stress of rebar	= 60,000 psi
	f'_c	= compressive strength of concrete	= 4,000 psi
	Ψ_e	= coating factor	= 1.0
	λ	= concrete weight factor	= 1.0
	d_b	= diameter of rebar	= .875 in

Equation 3. Hook development length calculation (ACI 2005)

A+ Engineers confirms hooks are viable alternatives for T-heads in terms of code requirements, as the boundary element is longer than l_{dh}. The owner applies their selection criteria to the three received bids and decides to hire Fabricator A. The owner then directs A+ Engineers to work with Fabricator A to select a rebar development detail. A+ Engineers and Fabricator A use AHP to compare three alternatives: (1) hooks, (2) Lenton T-heads, and (3) HRC T-heads.

A+ Engineers and Fabricator A develop a list of criteria for AHP analysis:

Transportation compares how far Fabricator A needs to transport rebar. This includes shipping rebar to site, and any transport necessary to install terminators.

Code compliance compares whether or not an alternative meets ACI 318 requirements.

Ease of placement compares how easily the rebar can be placed, given the fabricator's placement crew and capabilities.

Congestion addresses how much rebar needs to be placed in a given volume for each of the alternatives.

Strength development assesses whether or not each alternative provides a means for rebar to develop its strength.

Ease of detailing compares how easily the fabricator can detail each alternative.

Figure 13 shows the four-level hierarchy that illustrates criteria and their sub-criteria. The hierarchy in Figure 13 adds a criterion to those listed above, Fabricator capabilities, that has a similar level of detail as the criterion 'Code compliance.' By convention, criteria listed directly below the goal, i.e., 'Fabricator capabilities' and 'Code compliance,' are referred to as 'level-1 criteria.' Criteria immediately below 'level-1 criteria' are referred to as 'level-2 criteria,' etc.

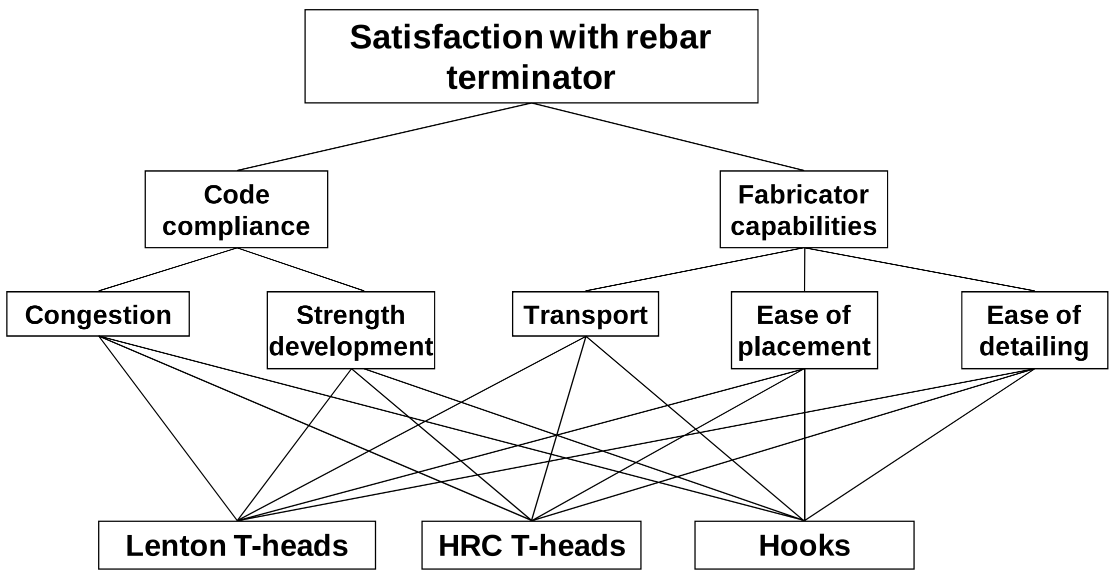


Figure 13. Four-level rebar terminator hierarchy

Table 7 and Table 8 show the comparison matrices and local priorities for each criterion relative to the other one (or ones, should there be more). The author assigned the values, respectively ⅓ (Table 7), and ⅕, ½, and 7 (Table 8) in the comparison matrices based on her background and experience with these criteria and the weights given in Table 5. She considers Code Compliance to be moderately more important than Fabricator Capabilities, so she weights Fabricator Capabilities as ⅓ relative to Code Compliance. She considers Ease of Placement to be essential, so she weighs this as 5, relative to Transport, which she assigns a weight of 1. She considers Ease of Detailing of almost equal importance to Transport, so she weighs Ease of Detailing as 2. She weighs Ease of Placement as 7, as its importance dominates over Ease of Detailing in projects. Finally, she weighs Congestion as 1 and Strength Development as 5 because Strength Development affects the structural performance, and therefore the structure's safety.

Table 7. Pair-wise comparison matrix and priority vector for 'level-1 criteria'

Criteria	Fabricator Capabilities	Code Compliance	Priority vector
Fabricator capabilities (FC)	1	1/3	0.25
Code compliance (CC)	3	1	0.75

Table 8. Pair-wise comparison matrix and priority vector for 'level-2 criteria'

Fabricator capabilities (.25)	Transport	Ease of Placement	Ease of Detailing	Priority vector	Code compliance (.75)	Congestion	Strength Developmen	Priority vector
Transport (T)	1	1/5	1/2	0.11	Congestion (C)	1	1/5	0.17
Ease of placement (EP)	5	1	7	0.74	Strength development (SD)	5	1	0.83
Ease of detailing (ED)	2	1/7	1	0.15				

Table 9 shows the comparisons between the alternatives themselves with respect to the 'level-2 criteria.' Note the comparison between the two T-head terminator alternatives, 'Lenton T-heads' and 'HRC T-heads.' The 'Transport' comparison matrix lists Lenton T-heads as 9 times better than 'HRC T-heads' with respect to transport. This reflects that

Fabricator A can install Lenton T-heads in-house, rather than sending rebar 854 miles (round-trip) to have HRC T-heads installed. Otherwise, the decision-makers rate the terminators equally. Hooks can cause placing difficulty, as they cannot be easily threaded through other bars. Further, detailing hooks can be challenging because the hook may not lie in the same plane as the rest of the longitudinal bar due to tolerance issues in bending and placing, so developing accurate placing drawings can be difficult. Despite difficulty detailing hooks, the hooks considered in this analysis do provide enough anchorage into the joint for rebar to develop its strength. Thus, the decision-makers listed equal weights for all alternatives in the 'Strength development' comparison matrix.

Table 10 lists the global weights of the alternatives. Based on this analysis, the decision-makers select the 'Lenton T-heads' alternative, as it earned the highest score.

A sensitivity analysis is in order. If the decision-makers had decided the Lenton T-heads were only 8 times better than the HRC T-heads with respect to transport, the two T-head alternatives would earn the same score, despite the larger lead time required for the fabricator to deliver the HRC T-heads. This AHP analysis reveals the importance of considering multiple stakeholders' perspectives through criteria. The structural engineers alone may not have considered the 'Transport' criterion, as they could have been unaware HRC requires their T-heads be installed in their LA facility. Further, the structural engineer designs a structure not knowing which fabricator will build the job. Thus, she must provide details that any allow multiple fabricators to bid on the job. HRC installs T-heads at their own facility, so any fabricator could bid on the job and send rebar to HRC for T-head installation. Finally, the structural engineer would not necessarily know whether or not a given fabricator has the equipment to install the Lenton T-heads, so even if the fabricator was part of the project team during design, the structural engineer may opt to specify HRC T-heads that she knows any fabricator could provide.

Similarly, the fabricators may be unaware of code requirements, so they may not have weighted ‘Code compliance’ or ‘Strength development’ as high as the author did.

Table 9. Comparison matrices and local weights for the rebar terminator alternatives

Fabrication capabilities (.25)					Code compliance (.75)				
Transport (.11)					Congestion (.17)				
	LEN	HRC	HO	Priority vector		LEN	HRC	HO	Priority vector
Lenton (LEN)	1	9	1	0.58	Lenton (LEN)	1	1	7	0.47
HRC	1/9	1	9	0.28	HRC	1	1	7	0.47
Hooks (HO)	1	1/9	1	0.14	Hooks (HO)	1/7	1/7	1	0.07
Ease of placement (.74)					Strength development (.83)				
	LEN	HRC	HO	Priority vector		LEN	HRC	HO	Priority vector
Lenton (LEN)	1	1	9	0.47	Lenton (LEN)	1	1	1	0.33
HRC	1	1	9	0.47	HRC	1	1	1	0.33
Hooks (HO)	1/9	1/9	1	0.05	Hooks (HO)	1	1	1	0.33
Ease of detailing (.15)									
	LEN	HRC	HO	Priority vector					
Lenton (LEN)	1	1	5	0.45					
HRC	1	1	5	0.45					
Hooks (HO)	1/5	1/5	1	0.09					

Table 10. Local and global priorities for rebar terminator alternatives

	Fabrication capabilities 0.25			Code compliance 0.75		
Alternative	Transport 0.11	Ease of placement 0.74	Ease of detailing 0.15	Congestion 0.17	Strength development 0.83	Weight
Lenton T-heads	0.58	0.47	0.45	0.47	0.33	0.39
HRC T-heads	0.28	0.47	0.45	0.47	0.33	0.38
Hooks	0.14	0.05	0.09	0.07	0.33	0.23

The author also considered the Choosing By Advantages Decisionmaking System.

2.4.2 CHOOSING BY ADVANTAGES (CBA)

Suhr (1999) developed CBA at the U.S. Forest Service to help make resource allocation decisions involving multiple stakeholders.

2.4.2.1 Description of CBA

CBA defines a vocabulary for use in the decision-making process. CBA trainers insist on its consistent use to make sure all people involved in the decision-making process are "speaking the same language." CBA defines alternative, factor, criterion, attribute, and advantage for use in the decision-making system. Table 11 shows these in tabular format. Decision-makers populate this table during the CBA process.

An alternative is a possible decision (e.g., choose alternative 1 or alternative 2). A factor is a container for criteria, attributes, advantages, importance, and other types of data (Suhr 1999). A criterion is a decision rule or guideline established by the decision-maker(s). A criterion may be a 'must' criterion, representing conditions that have to be satisfied, or 'want' criterion, representing preferences of one or multiple stakeholders. If an attribute of an alternative does not meet a 'must' criterion, the alternative is eliminated and no longer considered. An attribute is "a characteristic, quality, or consequence of *one* alternative." An advantage is a beneficial difference between *two* and only *two* attributes. Only advantages are expressed in the CBA system. No disadvantages are considered as such, i.e., a disadvantage of one alternative is listed as an advantage of another.

Table 11. Schematic CBA Table

FACTORS	**ALTERNATIVES**		
	ALTERNATIVE A	**ALTERNATIVE B**	**ALTERNATIVE C**
1. Factor 1 Must Criterion: Condition that must be satisfied related to Factor 1 Want Criterion: Preference of one or multiple stakeholders			
Attributes:	Attribute of A with respect to Factor 1	Attribute of B with respect to Factor 1	Attribute of C with respect to Factor 1
Advantages:			
2. Factor 2 Must Criterion: Want Criterion:			
Attributes:	Attribute of A with respect to Factor 2	Attribute of B with respect to Factor 2	Attribute of C with respect to Factor 3
Advantages:			
TOTAL IMPORTANCE:			

Table 12 maps the relationship between the AHP and CBA vocabularies. Note the CBA vocabulary defines more terms. Also note ‘Criteria’ in AHP maps to both the factors and the criteria in CBA, highlighting potential ambiguity in AHP. AHP does not have comparable terms to the CBA terms attribute, advantage, and importance, which highlights the greater nuance possible when using the vocabulary of CBA. ‘Priority’ in AHP refers to the comparison of criteria. CBA does not compare factors or criteria, so it does not have a comparable term. Also, note ‘Weight’ in AHP refers to a comparison of alternatives with respect to a given criteria. CBA compares alternatives by comparing the importance of advantages, so it does not have a comparable term to ‘Weight.’ However, the ‘Weight’ in AHP may correspond to the importance assigned in CBA, as ‘Weight’ does consider relative importance, but of *alternatives*, not *advantages*.

Table 12. Language mapping between AHP and CBA

AHP Term	CBA Term
Alternative	Alternative
Criterion	Factor
Criterion	Criteria
-	Attribute
-	Advantage
-	Importance
Priority	-
Weight	-

CBA consists of five phases: (1) the Stage-Setting Phase, (2) the Innovation Phase, (3) the Decisionmaking Phase, (4) the Reconsideration Phase, and (5) the Implementation Phase. The third phase is the primary subject of Suhr's 1999 book, *The Choosing By Advantages Decisionmaking System.* Phase 3 comprises four steps: (1) Summarize the attributes of each alternative, (2) Determine the advantages of each alternative, (3) Assign a degree of importance to each advantage, and (4) Choose the alternative with the greatest total importance of advantages.

CBA anchors decisions to relevant facts and postpones value judgment until the last responsible moment, the moment when failing to make a decision eliminates an alternative (Poppendieck 2000). Stakeholders agree on a set of alternatives to consider and decide on applicable factors on which to base their decision. 'Want' criteria reflect stakeholder preference, which may vary among stakeholders (i.e., Stakeholder A and Stakeholder B may have different preferences). However, creating multiple factors with different criteria can postpone value judgments until later in the decision-making process. Summarizing attributes consists of listing objective facts or data about each alternative, thus anchoring the decision-making process to relevant facts. Attributes are inherent to an alternative, so this step avoids subjective judgment. Determining the advantages of each alternative depends on the criteria that pertain to a given factor, but does not require subjective judgment (criteria reflect judgment). Assigning a degree of importance to each advantage is the first subjective task that requires stakeholders apply judgment to decide the relative importance of each advantage.

When assigning a degree of importance to each advantage, first highlight the most-important advantage in each factor, second, select the *paramount advantage*, the most-important of the most-important advantages. The paramount advantage is used to set the importance scale. CBA requires a common scale of importance be used to minimize the likelihood of ambiguity in the decision-making process. The lowest importance is zero, which denotes ‘no advantage.’ The paramount advantage takes the highest spot on the importance scale. Usually, the importance scale is sufficient to capture stakeholder opinions if the paramount advantage is assigned an importance of 100; however, in some cases, the range of advantages may warrant another importance (i.e., 10 or 1,000). To determine the paramount advantage, compare the most-important advantages in each factor and select the most-important of these most-important advantages (Suhr 1999). Third, weigh the importance of the most-important advantage in each factor, compared to the paramount advantage. Finally, assign a degree of importance to the remaining advantages relative to the paramount advantage. Involving multiple stakeholders in assigning a degree of importance to advantages allows decision-makers to consider multiple viewpoints. Further, if all stakeholders are included in determining the importance of advantages, they can explain their decision (and defend it if necessary).

CBA considers cost separately from other factors. CBA considers cost when two alternatives have different costs and the cheapest alternative is not also the most-preferred based on the step (4) analysis (e.g., the cheapest alternative does not have the highest total importance of advantages). Money is described in the CBA system as “an official message that serves as a medium of exchange.” This definition recognizes that the value of a dollar may vary depending on the amount of capital a decision-maker has, the tradeoffs associated with spending a dollar one way versus another way, and the decision-maker’s view of debt (Grant 2007). Decisions involving cost are made using a similar process to the one described above, detailed by Suhr (1999, pp. 242-259).

CBA has been used for group decision-making by the National Park Service (Suhr 2009), choosing a home (Adams 2003), and for selecting a green roof (Grant 2007). In addition to the example presented here, Chapter 5 presents an example of CBA for rebar design decision-making.

2.4.2.2 CBA Example: Selecting a Rebar Terminator

To illustrate CBA, the author re-visits the terminator alternatives detailed in Section 2.4.1.2. This example compares the same three rebar terminators, i.e., Lenton T-heads, HRC T-heads, and hooks. It also uses the same metrics for comparison, in this case, factors (Table 13). However, rather than using two levels of factors, CBA uses only the ‘level-2 criteria’ from AHP as factors, as these allow decision-makers to compare alternatives with minimal abstraction. That is, a factor like ‘Code compliance’ may be ambiguous, and it may be difficult to be objective when distinguishing differences between alternatives. Thus, CBA decision-makers split this factor into two new factors, ‘Congestion’ and ‘Strength development.’ Similarly, CBA replaces the AHP-criterion ‘Fabricator capabilities’ with three factors, i.e., ‘Transport,’ ‘Ease of placement,’ and

‘Ease of detailing.’ As is the case in Section 2.4.1.2, the data in Table 13 reflects the author’s background and experience.

Table 13. CBA Table for the rebar terminator alternatives

FACTORS	**ALTERNATIVES**					
	Lenton T-heads		**HRC T-heads**		**Hooks**	
1. Congestion						
Must Criterion: Concrete must be able to enter the beam-column joint						
Want Criterion: Less congestion is better (The more room in the joint, the better)						
Attributes:	3.9 in^3/bar		3.9 in^3/bar		<u>4.2 in^3/bar</u>	
Advantages:	.3 in^3 less volume	75	.3 in^3 less volume	75		
2. Strength development						
Must Criterion: The alternative must allow the rebar to develop its strength						
Attributes:	Develops strength		Develops strength		Develops strength	
Advantages:	No advantage of any alternative					
3. Transport						
Want Criterion: Less transport is better						
Attributes:	39 miles		<u>893 miles</u>		39 miles	
Advantages:	854 fewer miles	85			854 fewer miles	85
4. Ease of placement						
Want Criterion: Prefer to place bars that can be threaded between boundary element bars						
Attributes:	Easy placement		Easy placement		<u>Difficult placement</u>	
Advantages:	Easier placement	100	Easier placement	100		
5. Ease of detailing						
Want Criterion: Faster detailing is better						
Attributes:	.5 minute/bar to detail		.5 minute/bar to detail		<u>1 minute/bar to detail</u>	
Advantages:	.5 minute/bar less	20	.5 minute/bar less	20		70
TOTAL IMPORTANCE:		280		195		155

The factor ‘**1. Congestion’** pertains to the volume of rebar added to the joint in an alternative. For example, hooking a #7 bar into a joint requires 7 extra inches of rebar in the joint, totaling 4.2 in^3 of additional rebar volume. The ‘must’ criterion states that concrete must be able to enter the joint. The decision-makers can calculate the total volume of the rebar terminators in the joint and ensure space remains for concrete. The ‘want’ criterion expresses the preference of A+ Engineers and Fabricator A to minimize congestion in the joint.

The factor ‘**2. Strength development**’ pertains to the ability of each alternative to provide space for the rebar to develop strength. The ‘must’ criterion states that an alternative can be considered feasible only if it facilitates the development of the rebar strength.

The factor ‘**3. Transport**’ pertains to the number of miles the rebar must travel from Fabricator A’s shop to the site including any travel necessary to install T-heads. This factor does not have a ‘must’ criterion. The ‘want’ criterion states Fabricator A’s preference for shorter distance to travel, as this requires less time and cost.

The factor ‘**4. Ease of placement**’ pertains to the ease of placing the rebar terminators. The ‘must’ criterion states the fabricator’s requirement that he be able to place bars. The ‘want’ criterion expresses Fabricator A’s preference for placing straight bars in the joint because these can be threaded between longitudinal bars in the boundary element.

The factor ‘**5. Ease of detailing**’ pertains to the ease of detailing the rebar terminators. This factor does not have a ‘must’ criterion. The ‘want’ criterion expresses Fabricator A’s preference for detailing T-heads, as T-head suppliers often provide standard details for them.

2.4.2.2.1 Summarize the Attributes of Each Alternative

Table 13 lists attributes of each alternative, appertaining to each factor. An attribute reflects data wherever possible. For example, within the ‘Transport’ factor, the attributes of each alternative list the miles a piece of rebar travels from the fabrication shop to the project site, including any mileage necessary for T-head installation and delivery.

2.4.2.2.2 Determine the Advantages of Each Alternative

Table 13 lists the dissimilarities or differences that make up the advantages (Suhr 1999). Advantages reflect the backgrounds, expertise, and opinions of the stakeholders who determine them.

Table 13 reflects the author's identification of factors, criteria, attributes, and advantages. Another group of stakeholders may fill these elements of the CBA table differently, e.g., in factor '4. Ease of Placement,' they may gauge the advantage of 'Easy placement' compared to 'Difficult placement' to be 'Much easier placement' In lieu of 'Easier placement.'

2.4.2.2.3 Assign a Degree of Importance to Each Advantage

To assign the relative importance of each advantage, highlight the most-important advantage in each factor (gray-shaded cells in Table 13). From amongst the most-important advantages, select the most important most-important advantage. This is the paramount advantage, used to establish a scale of importance. The paramount advantage in this case is 'Easy placement' in the factor '4. Ease of placement.' The author assigned this advantage an importance of 100 (circled on Table 13). Decision-makers establish other importances relative to this scale. That is, they compare the most-important advantage in each factor to the paramount advantage, assign the most-important advantages an importance relative to the paramount advantage, and then assign a degree of importance to the remaining advantages in each factor.

2.4.2.2.4 Calculate Total Importance of Advantages

The last step is to total the importance of advantages of each alternative to identify the preferred alternative. The bottom row of Table 13 lists the total importance for each alternative. Lenton T-heads (Total importance = 280) are the preferred alternative based on the author's rationale.

2.4.3 Comparison of AHP and CBA Systems for the Rebar Terminator Example

The rebar terminator example was developed to gain experience with and illustrate the differences between the AHP and CBA decision-making systems. In both cases, the systems suggest the decision-makers select the Lenton T-heads as rebar terminators. Both systems also illustrate the importance of considering multiple stakeholders, as they bring different alternatives, factors, criteria, and advantages to the fore.

However, the margin between Lenton T-heads and HRC T-heads varies between AHP and CBA. In AHP, changing the weight of Lenton T-heads compared to HRC T-heads with respect to transport from 8 to 9 makes the alternatives 'equal.' Changing the weight by 2 reverses the decision and makes HRC T-heads the preferred alternative. In contrast, CBA requires specific factors advantages be listed and compared. This way, decision-makers 'see the whole picture' when assigning a degree of importance rather than comparing how two alternatives perform with respect to one factor and assigning importance independently (as in AHP). This makes the decision-making process more explicit and transparent.

In CBA, by comparing advantages of specific alternatives one on one, all stakeholders discuss the same advantage. By contrast, in AHP, decision-makers weigh criteria (which would be called factors in CBA) relative to one another. This can cause confusion, as criteria represent high-order abstractions. Typically, when weighing criteria, each stakeholder's mind defines the objective, or anchors it, to something. Problems arise when stakeholders anchor the objective to different things, and thus give objectives different weights. CBA reduces this ambiguity by directly comparing advantages. Further, CBA requires a common scale of importance be determined, so ambiguity is less likely in the decision-making process.

Researchers and practitioners use and develop tools in conjunction with decision-making systems to navigate the design process.

2.5 DESIGN TOOLS

Tools have been developed by researchers and practitioners to aid in various design process tasks. These tools are used in the AEC industry, as well as in manufacturing, new product development, and mechanical engineering. Table 14 lists some of these design tools. Tools of particular relevance to this dissertation are explained in more detail below.

2.5.1 A3 DOCUMENTS

A3 documents, named for the paper size they are presented on (roughly 11" x 17"), establish "a concrete structure to implement PDCA [Plan-Do-Check-Act] management" (Sobek II and Smalley 2008). Toyota engineers display measures taken in each phase of the Plan-Do-Check-Act cycle (Deming 1986; 2000; Shewhart 1939) in A3 documents. In this way, they serve as decision-making aids. A3s are being used as a communication and decision-making tool for the Cathedral Hill Hospital project (see Chapter 7), providing the decision-makers with information relevant to a given decision.

Table 14. Design tools

Design Tool	Reference	Used in AEC?	Used in other industries?
A3 Documents	(Morgan and Liker 2006; Shook 2008; Sobek II and Smalley 2008)	Yes (e.g., Parrish et al. 2009)	Yes
BIM	(Eastman et al. 2008)	Yes	Yes
Design Structure Matrix	(Steward 1981)	Yes (e.g., Tuholski and Tommelein 2008)	Yes
Discrete Event Simulation	(Law and Kelton 2000)	Yes (e.g., Tommelein 1998)	Yes
Last Planner™	(Ballard 2000a)	Yes (e.g., Ballard 2000a)	Yes, as the "complete kit"
Process Mapping	(Damelio 1996)	Yes (e.g., Polat and Ballard 2003)	Yes
Quality Function Deployment	(Clausing 1994)	Yes (e.g., Gargion 1999)	Yes
Target Costing	(Ulrich and Eppinger 2004)	Yes (e.g., Ballard 2006)	Yes

Sobek II (2008) enumerates the steps of the problem-solving A3 process: (1) Identify a problem or need, (2) Conduct research to understand the current situation, (3) Conduct root cause analysis, (4) Devise countermeasures to address root causes, (5) Develop a target state, (6) Create an implementation plan, (7) Develop a follow-up plan with predicted outcomes, (8) Discuss plans with all affected parties, (9) Obtain approval for implementation, (10) Implement plans, and (11) Evaluate the results. Toyota uses A3s throughout organizational levels as communication tools (Morgan and Liker 2006). At Toyota, developing an A3 report is a discipline. Its purpose is not merely to produce a piece of paper that documents a PDCA cycle; more importantly, it is to support people within an organization as they explore options and develop arguments for discussion. A3s document and support learning and establish "a concrete structure to implement PDCA management" (Shook 2008; Sobek II and Smalley 2008, p. 11). Figure 14 illustrates a template for an A3 report. Theme introduces the content to the audience. Background presents “pertinent… information… essential for understanding the extent and importance of the problem” (Sobek II 2008). Current Condition gives an overview on the current state, highlighting key factors in it, and identifying major issues with quantitative measures. Cause Analysis illustrates the causes of the major issues presented in the Current Condition and shows why these conditions can be or need to be improved. Target Condition sets out countermeasures to the causes of the major issues, and measurable objectives to determine the success of these countermeasures. Toyota engineers use the term ‘countermeasures’ (as opposed to, e.g., ‘problem solutions’) to amplify that they anticipate challenges and proactively work to preempt problems. One example of such proactive engagement is their practice of ‘poka yoke’ or ‘mistake-proofing’ (Tommelein 2008). Implementation Plan addresses the who, what, when, and where questions associated with the countermeasures suggested in Target Condition. Finally, the Follow-Up section contains a plan, explaining how and when effects of the implementation of countermeasures will be recorded. Actual Results displays the results of countermeasures insofar as they are available when the A3 is produced (Sobek II and Smalley 2008). A3s also typically include an Approvals section, consisting of supervisor signatures, which confirms the A3 report has been discussed and the Implementation Plan approved (Sobek II and Smalley 2008).

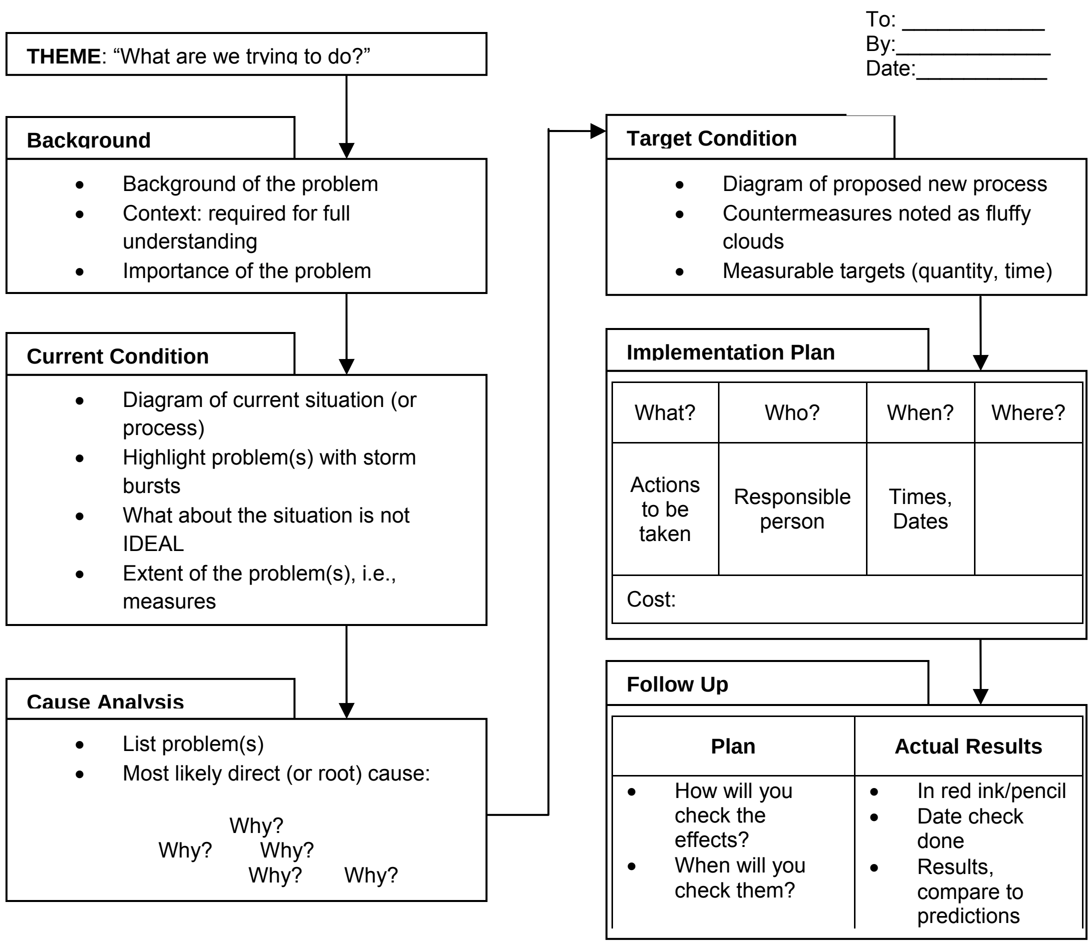


Figure 14. A3 Report Template (available at http://www.coe.montana.edu/ie/faculty/sobek/a3/report.htm)

Morgan and Liker (2006, p. 274) suggest these "Vital points" when preparing A3 reports:

1. Plan time to grasp the ENTIRE situation
   a. Consider a wide range of information sources
   b. Base story on facts not opinions
   c. Consider the long-term effect
2. Decide what kind of story you need to tell. Write to your audience. Consider their needs and knowledge of the situation.
3. Relate the story to company values and philosophy.
4. Make the story flow in logical sequence.
5. Save words. Use graphs and visuals to tell your story whenever possible.
6. Make every word count. Be specific and avoid jargon.
7. Consider the visual effect of each box on the page in helping you tell your story.

2.5.2 DESIGN STRUCTURE MATRIX (DSM)

Often, engineers divide complex systems into smaller subsystems which are easier to understand (Browning 2001). The design structure matrix (DSM) is one way to split a complex design process into discrete pieces. Project-based DSMs (as opposed to parameter-based DSMs) “assist in understanding activity inter-relationships and dependencies” (Tuholski 2008). Understanding dependencies helps identify positive and negative iteration in the design process, and determine an activity sequence that minimizes its negative iteration and supports efficiency (Browning 2001). The DSM “can be used to develop an effective engineering plan, showing where estimates are to be sued, how design iterations and reviews are handled, and how information flows during the design work” (Steward 1981). Figure 15 shows sample DSMs that model different kinds of task dependencies. Marks that are non-symmetrical relative to the diagonal indicate a precedence relationship. For example, Figure 15 illustrates Task 4 being dependent on Task 3. More generally, one could say, “the activity in the i^{th} row is dependent on the activity in the j^{th} column.” Precedence relationships indicate a transfer of information between team members or activities. Marks that are symmetrical relative to the diagonal indicate mutual dependency between activities.

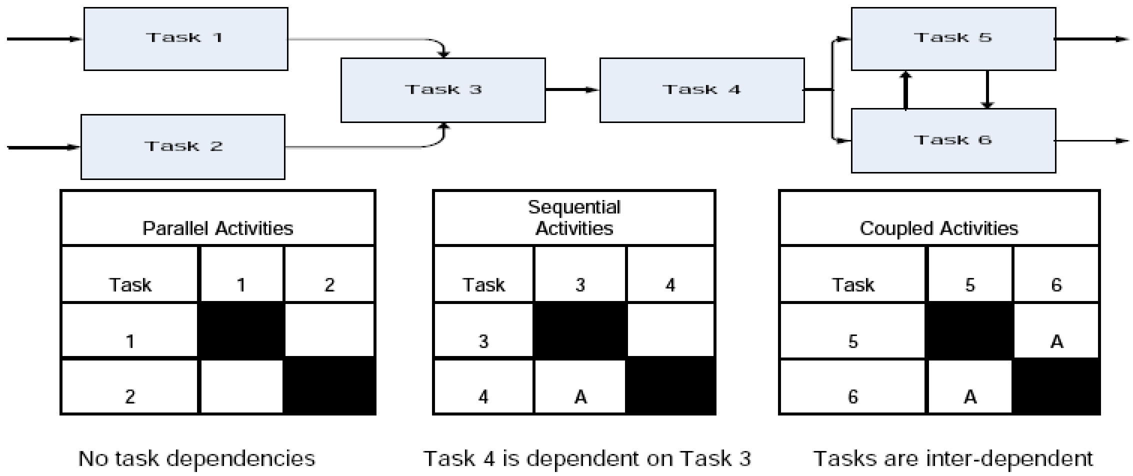


Figure 15. Sample DSM (Figure 1 in (Tuholski and Tommelein 2008)

The DSM modeling process consists of four steps: two steps to represent the process as a DSM, and two steps that optimize the process (Tuholski 2008).

Step one involves dividing the system into a set of discrete activities. To do so, modelers must determine the system boundaries and consider activities in keeping with these boundaries. Browning (2001) recommends decomposing the process to the level of detail to which one desires to understand and control the process. Modelers should document inputs to and outputs from activities when decomposing the system into a set of activities.

Tuholski (2008) describes step two:

> Step two arranges activities sequentially in a square matrix with identical row and column identifiers. Numeric (or binary, e.g., using an X or a 1) marks at row and column intersections identify a dependence relationship between activities. Weighted numeric dependencies are often characterized by A, B, and C demarcations indicating very strong, strong, and weak dependencies. The absence of a mark shows no dependence.

Step three, often referred to as sequencing, involves analyzing and manipulating the matrix to develop a more optimal process. Kusiak (1999) describes a manual method for sequencing, and Browning (2001) describes an automated method. Marks below and to the left of the diagonal represent feed-forward dependency between activities and imply a linear process. Marks above the diagonal indicate iteration and feed-back dependency. Activities within these feed-back dependencies make up a so-called ‘iteration block.’ Iteration is inherent in design, so marks will often fall above the diagonal in a DSM describing a design process. Iteration blocks require attention from designers and schedulers, as these hinder linear progression through the process. Alternatively, design can progress with incomplete information, as recommended by set-based design, to proceed through the iteration loop. The goal of sequencing is to make the DSM as linear as possible and re-sequence activities to minimize iteration blocks.

Step four, tearing, involves breaking the iteration blocks. To do this, dependencies need to be released, e.g., by making assumptions (preferably the final design is insensitive to these assumptions), or by decomposing or aggregating activities to reduce the dependencies between activities. After tearing, iteration blocks should be more linear.

Another tool that helps designers visualize and understand processes is process mapping.

2.5.3 Process Mapping

Process mapping is a method used to visualize the flow of material as well as the links between and beyond the single process level (Rother and Shook 2003). Examples of process mapping methods include value stream mapping (Rother and Shook 2003; Womack et al. 1990b) and the development of cross-functional diagrams or swimlane diagrams(Damelio 1996). Process maps can show the flow of material and information from customer order through customer delivery; they can facilitate the identification of waste and its root causes (Arbulu and Tommelein 2002).

2.5.3.1 Cross-Functional Diagrams

“Cross-functional maps [diagrams] illustrate how work gets done in organizations” (Damelio 1996). Cross-functional diagrams illustrate processes and are thus useful in visualizing work flows, information flows, and/or material flows. Chapter 4 presents an excerpt of a cross-functional diagram of the current state of the rebar design and delivery system. Cross-functional diagrams organize supply chain participants and project stakeholders along the left-hand side, into ‘lanes’, hence the name swimlane diagrams. Arrows between lanes show dependencies between supply chain participants. In addition to illustrating dependencies in systems, cross-functional diagrams allow researchers to visualize handoffs and potential wastes in them.

Appendix A shows a cross-functional diagram documenting the flow of material from “cradle to placement” that the author used to develop a set-based methodology for rebar design. This cross-functional diagramming effort began in 2003 and that map was further developed in 2007. Industry participants in the author’s research and academics in the fields of structural design and project management reviewed the map for accuracy and completeness. The map highlights the number of specialists involved in the rebar supply chain, the iteration in the current design process, and the volume and type of information that needs to be passed between stakeholders. Cross-functional diagrams illustrate opportunities for implementation of a set-based methodology for rebar design.

In addition to illustrating material flows, cross-functional diagrams illustrate information flows. Learning who needs what information at what time can be eye opening for the participants in the diagramming exercise. It becomes clear that participants pass on information they believe will be useful to the participants downstream e.g., it meets contractual requirements); however, they may not know what information their downstream participants actually need (Chapter 7 presents a case study that addresses this issue). Cross-functional diagrams also show the volume of information generated in a process and provide an opportunity to see how this information is either captured or lost. For instance, structural engineers calculate the area of rebar necessary in a given member, but this number may not be shared; rather, the structural engineer instantiates a rebar configuration in design drawings. Cross-functional diagrams highlight opportunities for information capture, and process improvements can take advantage of these opportunities.

People involved in a diagramming effort may examine the current state cross-functional diagram and develop a desired future state diagram. Future state cross-functional diagrams depict the improved process flows. Changes between the two states may include changes in flows, addition or removal of lanes, reduction of handoffs, and re-sequencing of activities. Cross-functional diagrams rarely show quantitative changes. By contrast, value stream maps illustrate process changes quantitatively.

2.5.3.2 Value Stream Mapping

Cross-functional diagrams focus on illustrating flows. Conversely, value stream maps “follow the product” and provide data to accompany the product’s flow illustrated in the map. Value stream mapping is a lean technique used to display all the actions or steps, both value adding and non-value adding, necessary to generate a product. Value stream maps are more data rich than their cross-functional counterparts, displaying data about value-added time (VAT), lead time (LT), and idle time in a product flow. Howell and Ballard (Howell and Ballard 1998) state that identifying the value stream establishes when and how decisions should be made; mapping brings choices to the surface and raises the possibility of maximizing performance at the project level.

A “Current State Map” is the term used for the initial process flow while a “Future State Map” is generated to improve that process. Implementation of the Future State Map should lead to increased flow of the material and reduced wasteful steps, thereby creating a leaner process (Rother and Shook 2003).

2.6 VALUE IN DESIGN

The set-based methodology developed in this dissertation seeks to add value to the design and construction process for the project stakeholders. To do this successfully, the value each stakeholder brings to the project and what they value from the project must be understood.

“Value... relates to assessments about products and can be subjective if they [values] remain internalized within an individual or an organization, or objective if they are expressed” (Thomson et al. 2003). Thomson et al. (2003) compare this definition to that of quality, “an assessment of how well its [the product’s or process’] qualities (that is its features or attributes) meet the customer’s needs” (Thomson et al. 2003). They go on to explain difficulties in distinguishing the two.

Project stakeholders are concerned with the quality and value of the design and construction of a structure. However, stakeholders may find it difficult to communicate their opinions on both quality and value. Stakeholders may not participate in a project early enough to provide useful input about quality and value. Moreover, they may lack a common language of value in construction (Thomson et al. 2003). Gann et al. (2003) developed the Design Quality Indicator (DQI) to "explicitly [to] measure quality of design embodied in the product – buildings themselves. It was not intended to assess the design process … [though it has] help[ed] inform design decision-making during the process." Figure 16 shows how the DQI aids in value conversations amongst stakeholders. The DQI can be measured throughout the design and construction process and be used as a feedback control. Thus, stakeholder values can be more readily incorporated into designs. Though the DQI has helped assess the design process, this is not its intended purpose, so it is not used in this dissertation.

Currently, construction project managers may try to incorporate value through a value analysis or value engineering, a process used extensively in construction projects to eliminate "unnecessary costs" (Cariaga et al. 2007). Cariaga et al. (2007) describe a method that uses a functional analysis system technique (FAST) and quality function deployment (QFD) in conjunction with the analytic hierarchy process (Saaty 1990) to determine alternative design options and assign these options a value. This method promotes a rational means of decision-making when considering multiple (possibly conflicting) objectives. While value engineering sessions have been criticized (Joshua Kardon, personal communication, 4/11/08) for being unproductive, Cariaga et al. (2007) offer a method to understand stakeholder values. This dissertation favors CBA, rather than the method described by Cariaga et al. (2007) to elicit stakeholder values.

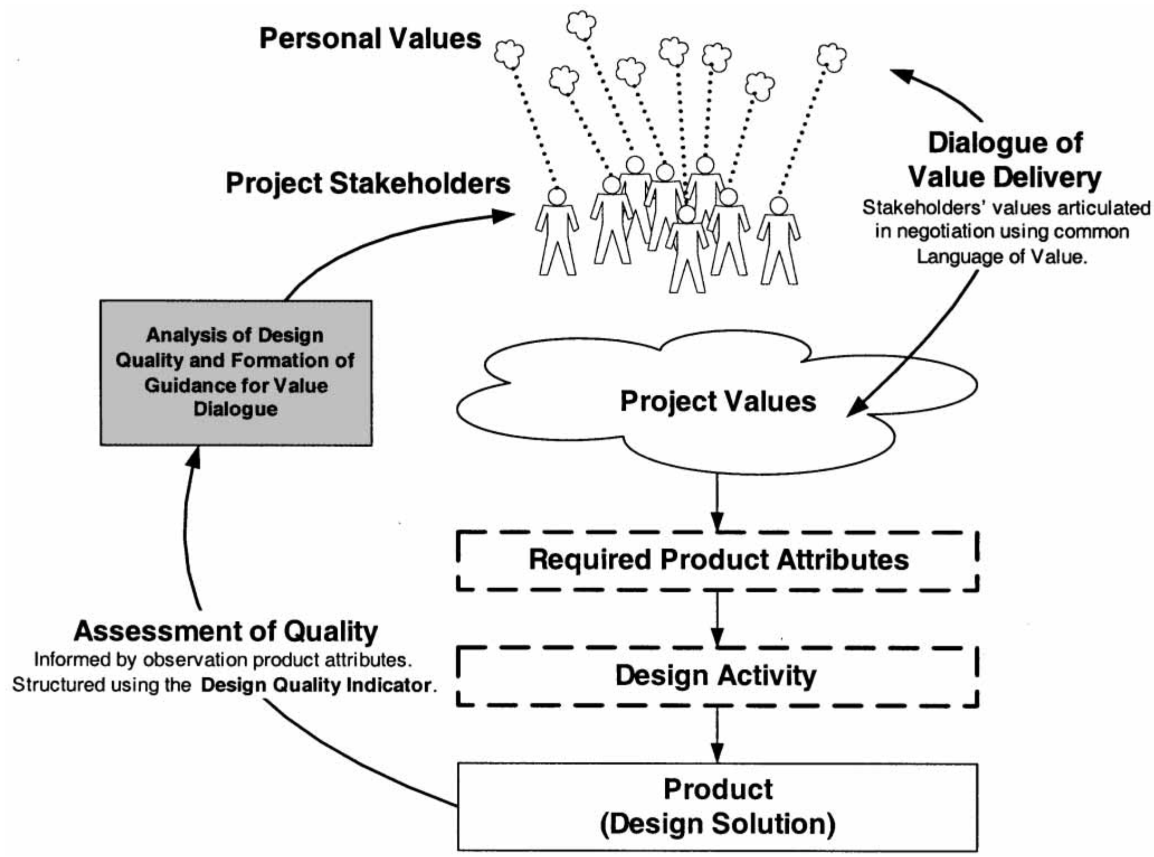


Figure 16. The role of the DQI in the value conversation (Figure 6 in Thomson et al. 2003)

2.7 SET-BASED METHODS

For the purposes of this research, a set is defined as a group of design alternatives at some level of detail, that can be defined either as discrete (e.g., specific rebar configurations) or continuous (e.g., a 24 in. deep beam, ± .1 in.). Literature does not support the existence of a formalized set-based methodology for rebar design. However, set-based methods exist for other uses as described next.

Duncan et al. (1987) used a set-based methodology to develop PROTEAN, a computer program used to describe the structure of proteins in solutions. Modeling abstractions make the problem of defining protein structure solvable. PROTEAN uses data about proteins as inputs, then uses a geometry system, a reasoning system, and a display system to display the structure of a protein in a solution. The geometry system "performs calculations for placing objects in space and checking that constraints are satisfied." The reasoning system uses Blackboard (BB1) architecture, which is also used in SightPlan (Tommelein 1989), to store problem specifications and emerging solutions. The Blackboard engages "knowledge sources" as the protein structure develops and postpones commitment to a specific solution, and instead develops and displays emerging solutions.

Tommelein (1989) uses a set-based methodology to determine construction site layout and describes the various methods that can be used to communicate the relationship between two rectangles (or site areas) in space. One finds it difficult to explicitly define this relationship with words due to the ambiguity of language (i.e., nearly does not specify an exact location). Thus, abstraction methods are necessary first to define site areas as rectangles and second to define the relationship between them. Like many problems in the AEC industry, site layout is both a communication and a knowledge problem. The inability to communicate accurately is not necessarily the fault of those communicating, but it is caused by the lack of specificity of the language. The knowledge problem deals with the lack of agreement between experts on a given subject. In order to solve the site layout problem, Tommelein (1989) "uses a simple representation of 2-dimensional space to reason about spatial constraints that need to be satisfied between rectangular objects in a layout." This representation is implemented in SightPlan with "a general architecture for reasoning about action, BB1."

Rebar design is also both a communication problem and a knowledge problem. The various project stakeholders have their own jargon, specific to their field or company. In terms of knowledge, there is no *one right* way to design rebar. Many factors and criteria, including objective facts and personal preferences, influence stakeholder assessments of a given rebar design alternative.

Ward (1989) explores the use of set-based methods for mechanical design. He explains sets are necessary because, “many important relationships [connect] … artifact sets, value sets, and operation conditions sets.” His dissertation explains the relationship between artifact sets and value sets in the context of mechanical system design. He programs a mechanical compiler to look through many mechanical design components (e.g., engines, valves, pumps) from one catalog and select compatible components. In order to do this, each component must be coded into the compiler. Ward’s work therefore differs from this author’s work, as this work does not restrict the design space to specific components. The author’s work seeks to build on the set-based methods introduced for design in Ward’s work by explicitly documenting relationships between value sets and artifact sets (design alternatives) and using them to inform the design process.

The new product development field is probably most similar to the rebar design field, as structural engineers are in essence developing a new product during the design phase. Toyota engineers used set-based methods for new product development, as described in Ward et al. (1995). Kennedy et al. (2008), Kennedy (2003), Ward et al. (1995)describe Toyota’s product development process as “set-based concurrent engineering,” focused on “delaying decisions, communicating ‘ambiguously,’ and pursuing excessive numbers of prototypes.” “Concurrent” refers to involvement of many disciplines at the same time. At Toyota, “designers explicitly communicate and think about sets of design alternatives at both conceptual and parametric levels. They gradually narrow these sets by eliminating inferior alternatives until they come to a final solution" (Ward et al. 1995).

A set-based methodology for rebar design involves multiple disciplines. It focuses on exploring many alternatives (the design space) at the conceptual level, but does not necessarily require development and testing of many prototypes. In structural design, it may not be feasible to physically build even one prototype, so designers use virtual models and virtual builds to compare prototypes. By contrast, building clay models of multiple prototype designs is common in the automobile product development cycle(Ward et al. 1995), though automobile manufacturers also use virtual models.

Use of set-based methods in product development is viewed as a key ingredient of Toyota's economic success. Toyota's suppliers also practice set-based design (Liker et al. 1996). Toyota engineers examine many designs at the project outset and continually tests these designs to ensure that all designs considered are robust; that is, each design can be successful in a variety of environments (Liker 2004). When the designers are confident they have explored a sufficient number of robust design alternatives, they begin to narrow sets. Toyota's company culture requires new designs not be considered once sets begin to be narrowed. That is, when a set begins to be narrowed, it is "locked", and can no longer be expanded (i.e., the designers avoid backtracking). A 'Lessons Learned' book captures knowledge used to narrow sets. This book is available as a reference to any employee who needs or wants to review a given design. To "unlock" a set of alternatives, an engineer must provide a new alternative *not* documented in the Lessons Learned book. Lessons Learned books support organizational learning for use in future design efforts.

Sobek et al. (1999) fleshed out three principles that govern set-based concurrent engineering as practiced at Toyota: (1) Map the design space, (2) Integrate by intersection, and (3) Establish feasibility before commitment. The first principle focuses on determining what constitutes a feasible design space from the perspective of each discipline. Once determined, each discipline develops sets of feasible design alternatives and shares it with all involved participants. The second principle focuses on narrowing the sets; determining the intersection of sets of feasible design alternatives results in the set of potential final designs. Developing a set of factors to consider, such as robustness, listing the criteria associated with these factors, and making selections further narrows the set of potential final designs. In order to reduce the set of feasible design alternatives to a final design, the participants gradually narrow the set while detail on the alternatives increase. They take care to ensure discussions center around the previously accepted set of feasible alternatives. This ensures participants spend their time effectively, and avoid rework insofar as possible. Finally, the third principle focuses on narrowing the set down to a single point, representing the final design that will be manufactured. Once Sobek II et al. (1999) fleshed out Toyota's principles, other researchers began to apply them in the AEC industry.

Lottaz et al. (1999) suggest using constraint-based problem solving to support collaboration between project participants. Specifically, they examine the fabrication of beams for a steel frame building with ductwork holes cut into them. They suggest all project participants use an internet-based collaborative tool to make decisions about the diameters and locations of ductwork holes. This internet tool tracks the constraints concerning ductwork as well as the abilities of each project participant to change diameter and location values. Implementing this web-based constraint solving system allowed for postponed commitment to specific diameters and locations, which in turn led to less rework on the project, as the steel fabricator was able to fabricate with reliable information rather than assume values that later changed. Terwiesch et al. (2002) describe the benefits of using a set-based methodology for design in terms of ambiguity and uncertainty. Schrader et al. (1993) Defined these terms as: uncertainty is knowing all the variables involved in a problem but not knowing their values, ambiguity is not knowing all of the variables involved in problem or the values of these variables. Terwiesch et al. (2002) explain why a set-based methodology for design works best in uncertain environments. They go on to explain that starvation (lack of work for the downstream participants) can occur as a result of too little detail in a set-based environment. The set-based methodology for rebar design developed in this dissertation tries to minimize the likelihood of starvation as a result of postponing commitments.

Ulrich and Eppinger (2004) also explored set-based design methods in new product development, referred to as 'structured methods.' They promote the use of structured methods for product development for three reasons:

> 1. They [structured methods] make the decision process explicit, allowing everyone on the team to understand the decision rationale and reducing the possibility of moving forward with unsupported decision.
>
> 2. By acting as "checklists" of the key steps in a development activity, they [structured methods] ensure that important issues are not forgotten.
>
> 3. Structured methods are largely self-documenting; in the process of executing the method, the team creates a record of the decision-making process for future references and for educating newcomers.

Liker (2004) explains Toyota's set-based practices are successful because they expand on a solution that is initially workable. He uses the development of the Prius as an example. While developing new engine technologies for the Prius, Toyota considered 80 hybrid engines initially and then narrowed the set down to ten (ibid p. 240). Toyota narrowed the set of ten options to four based on careful review of the merits of each hybrid engine. Though Toyota eventually selected one engine, four engines could have worked, providing Toyota the flexibility to study many engines while still being confident they would be able to release the Prius on schedule (Liker 2004).

Ford and Sobek (2005) explain the importance of set-based product design methods for adding latent values (those that remain hidden and often unexploited, e.g., prefabrication opportunities or fabrication abilities in the case of rebar design) to the product. They state "retaining flexibility in the form of options to change course can have value in the face of uncertainty" and they therefore advocate for the use of real options in product development. This is of particular interest in this work as the use of postponed commitment in a set-based methodology can reap these latent values.

Gil et al. (2008) discuss the need to preserve design flexibility, and thus, postpone commitment in large infrastructure projects. They develop a set of propositions detailing the use cases of iterative design, set-based design, buffers, and modularization. Gil et al. also use the notions of uncertainty and ambiguity defined by Schrader et al. (1993), to explain that iterative design is favorable when "they [upstream developers] believe that the assumed benefits of adapting their designs outweighs the costs." They go on to propose "upstream developers will not invest in set-based exploration when they expect downstream uncertainty and ambiguity to remain unresolved until late in the implementation of the upstream design." Rather, developers implement an iterative, point-based design approach in this case. Similar phenomena were observed on the Cathedral Hill Hospital project described in Chapter 6.

Parametric design software with AEC applications may help practitioners implement lean practices like set-based design. Parametric design software represents a form of BIM software—software that depicts “design as objects that carry geometry and attributes” (Eastman 2007).

Castro-Lacouture and Skibniewski (2006) studied parametric set-based design in civil engineering, applied to the rebar industry. They describe a “business-to-business [B2B] e-Work system” to foster collaboration between rebar suppliers, construction firms, and design firms. Their work illustrates a system for reducing task durations compared to existing work structures. The B2B e-Work system is implemented using an XML database and ASP. The services architecture in the B2B e-Work system involves specified tasks where each participant provides inputs and outputs based on shared information. This system provides mechanisms for tracking changes and allowing the contractors and structural engineers to make concurrent revisions to structural drawings. This mechanism represents a set-based approach to design iteration.

Nahm and Ishikawa (2006) develop parametric design software to aid in structural engineering. This program is similar to the compiler program developed in Ward’s dissertation (Ward 1989), in that it searches a database of possible design alternatives. The parametric design software uses a 3D Computer Aided Design (CAD) system for visualization and object-oriented programming to organize data in a database. Thus, the 3D graphical representation is a geometric rendering of the object, but the object itself is a set of data stored in the database. Further, the software solicits designer preference about alternatives and stores it in the database to aid in selection of the design alternatives for a given set of design constraints. This 3D-CAD program is similar to a software tool developed as part of this work that aids in set-based design, described in Chapter 8.

Parametric design is also used by BIM tools "to define objects… as parameters and relations to other objects, so that if a related object changes, this one will also. Parametric objects automatically re-build themselves according to the rules embedded in them" (Eastman 2007). Object-based parametric modeling methods, seen in most CAD systems today, were developed in the 1980s (Eastman et al. 2008). Since then, software designers created pre-defined building objects that they embedded in object-based BIM tools to generate 3D BIMs (Eastman et al. 2008). Set-based and parametric methods both define objects by specific attributes, rather than as specific pieces. For instance, in a BIM, a user can define an object as a beam (using the pre-defined object library), or a user can define a volume that is 24 inches deep and 18 inches wide without specifying it as a beam. Similarly, in set-based design, a user can define all beams between 22 and 26 inches deep and between 16 and 20 inches wide, without specifying the exact dimensions. Both methods use similar operators (e.g., union, intersection, and difference) to define new sets and objects, respectively, and monitor how these new sets and objects relate to previously-defined sets and objects.

This literature review provides a context for the author's research and contributions. This research develops a set-based DTM. The author considers the design process from a TFV perspective to determine where to apply set-based design methods. Further, she incorporates in these methods sound decision-making through CBA. Finally, the author's review of set-based design literature, her examples, and her proof-of-concept tool development work suggest that set-based design could be broadly applicable in the AEC industry.

CHAPTER 3. DESIGN THEORY AND METHODOLOGIES (DTM) QUESTIONNAIRE

The questionnaire presented in this chapter was a collaborative effort between the author and Dr. Stanislaus Tuholski while he was a graduate student at UC Berkeley in the Engineering and Project Management Program of the Civil and Environmental Engineering Department.

3.1 INTRODUCTION

This research explores the application of the emergent theory of design and construction within the AEC industry, the New Production Philosophy (a.k.a. Transformation-Flow-Value, TFV), to structural engineering design. Developing a deeper understanding of structural engineering DTMs in use today will facilitate future design process improvements.

We developed a questionnaire for academics and practitioners that asked them to describe design theory(ies) and methodology(ies) they teach and use. Responses to the questionnaire presented illustrate the current SE practices within the AEC industry. Current SE design theory and methodologies (DTMs) focus on engineering analysis within the Concept/Schematic Design and Preliminary Design/Design Development phases of the process (Figure 3) and make little, if any, mention of the remainder of it. They appear to not address the full range of requirements, values, and purposes (e.g., cost, constructability, production flows, value delivery, and supply chain logistics) that confront practicing structural engineers (SEs). Practitioners recognize the need to develop and implement improved methodologies, but they may lack the research and development resources necessary to make such advancements. Responses to the questionnaire also show practitioners did not have formal education and training in SE DTM. Rather, engineers cite mentorship, combined with experience gained on increasingly complex projects, as the primary means of learning.

Structural engineering academia focuses on analysis, leaving a void in the advancement of theories describing comparative concept selection, design space exploration, and project team interaction, among others. This view supports both the current structural engineering DTMs' focus on engineering analysis and the practitioners' stated lack of education about SE DTMs. Structural engineering design manuals and student handbooks describe point-to-point methods for design that characterize the design process as one of solving engineering problems by describing the system, identifying constraints, assigning fixed parameters, and optimizing variables. These methods ensure compatibility with the laws of mechanics and building codes; however, they provide little guidance on how to develop solutions that satisfy multiple stakeholders with competing values. Contemporary SE DTMs also lack guidance on project team interactions, including design activity sequencing (information flow), work structuring, and value management.

Synthesis of responses, from the perspective of TFV theory, reveals the AEC industry focuses on the transformation view of design, e.g., Critical Path Method (CPM) and Work Breakdown Structure (WBS) implementation, with little consideration of flow (e.g., information content, dependence, and hand-offs) and value (e.g., customer focus, alignment, and delivery). The SEs we questioned cited language barriers and skepticism toward transplanting DTMs rooted in manufacturing (i.e., Toyota Production System principles) as impediments to future SE DTM development. The same group of SEs, however, displayed an overwhelming willingness and interest to explore new team-oriented DTMs and leadership roles within the design process.

3.2 CLASSIFICATION OF DTMS

Historically, researchers explored DTMs through the study of manufacturing and new product development. Cross, in Waldron and Waldron (1996), defines the field of DTM research as:

> The study of how designers work and think; the establishment of appropriate structures for the design process; the development and application of new design methods, techniques, and procedures; and reflection on the nature and extent of design knowledge and its application to design problems.

An extensive body of literature is available on classification systems and summary descriptions of DTM research (Cross 2008; Finger and Dixon 1989a; 1989b; Krishnan and Ulrich 2001; Waldron and Waldron 1996; Wynn and Clarkson 2005). Table 15 and Table 16 present the summary of DTMs researched.

The questionnaire included these tables to gauge practitioner and academic exposure to the field. The taxonomy presented in this table provides a context for DTMs and a point of departure for future development and application of DTMs within SE design. It also extends the current classification of DTM research to include the emerging study of team- and production- system oriented methodologies.

3.3 QUESTIONNAIRE DEVELOPMENT

Salant and Dillman (1994) suggest that questionnaires, surveys, or both are appropriate research tools when researchers need “estimates of population characteristics.” The author, jointly with Stan Tuholski sought to characterize the current state of the SE industry in terms of DTM education or training with the questionnaire presented.

Salant and Dillman (1994) explain good questionnaires "make the task of responding as easy as possible." Further, questionnaires distributed via email must be attractive and of a reasonable length to ensure a good response rate. A questionnaire must also follow a logical progression of topics throughout its pages. The questionnaire used for this work did exactly this: the first page introduced the topic of DTM and asked respondents to comment on the current state of the SE industry based on their experience, the second page introduced a taxonomy of the literature on DTM, and the third page asked respondents for comment on that.

Thomas (1999) suggests structuring questionnaires around a central research question. Each question in the questionnaire should provide information necessary to answer that central question. The questionnaire used for the author's research consisted of only open-response questions. Thomas (1999) states ten guidelines for developing open-response questions: (1) Do not ask leading questions, (2) Do not use loaded words or phrases that suggest approval or disapproval, (3) Avoid social desirability in the questions, (4) Avoid suggesting a response, (5) Encourage critiques by sharing a concern, (6) Ask for information the respondent is likely to have, (7) Write items at the appropriate reading and understanding level of the respondent, (8) Communicate clearly to the target audience, (9) Create clear and concise questions, and (10) Clearly address one of the objectives you've created for the survey [questionnaire] project.

3.4 QUESTIONNAIRE

The questionnaire (Figure 17) comprises an introduction with background, a research DTM taxonomy table summarizing classical tools and methods, and a series of questions.

3.4.1 Statement of Purpose

The purpose statement of the questionnaire (P^2SL 2007) reads:

> There is a noticed lack of uniformity in Structural Engineering Systems Design. Our objective is to assess the current state of Structural Design Theory and Methodology from expert perspectives, in both academia and practice. Our future goal is to shape forthcoming contributions to the advancement of this field in a way that will maximize the value brought to practitioners while building on the theoretical knowledge base.

3.4.2 Profile of Respondents

Table 17 summarizes the diverse group of engineers who were asked to participate in the questionnaire research. This group includes accomplished practitioners with significant design experience and academics focused on DTM development and education. The authors solicited responses from structural engineers in the San Francisco, CA, Bay Area with 10 or more years of experience. A key element of the survey is to understand the education and training the engineers received, as well as training they administer about design methodology. Thus, only experienced engineers were questioned. Further, the respondents worked on high profile projects with innovative structural systems. It follows that these engineers may have been exposed to innovative design processes as well.

Design Theory & Methodology Questionnaire

Project Production Systems Laboratory – P^{2}SL
http://p2sl.berkeley.edu/
UC Berkeley
215 A McLaughlin Hall, Berkeley, CA 94720-1712

Introduction

Our literature review and preliminary case-study findings indicate that little or no formal education in design theory is available to the structural engineering community. Many structural engineering design texts suggest the use of point-to-point design methods but do not spell out formal processes or underlying theories. In this case, theory refers to a set of established axioms or documented observations governing the design of engineered products.

Recent research on design theory applied in structural engineering design appears focused on the application of the design structure matrix and concurrent engineering (methods which have yet to gain acceptance in practice). Research has also been conducted on the effects of experience on structural engineering systems design. Otherwise, the majority of contributions to design methodology development can be traced to sources outside of the field of structural engineering, namely the fields of mechanical engineering and new product development.

Because the design and integration of civil systems into our natural world is becoming exceedingly complex, projects often require sophisticated co-development with cross-functional teams. This new generation of projects can benefit from cogent, theoretically-based methodologies to facilitate design and project delivery processes.

To explore design alternatives, our research group is studying the application of set-based, concurrent engineering strategies to develop structural engineering systems much in the way Toyota develops new products and production systems. To better understand how this new thinking compares and contrasts with current design theory and practice in structural engineering, we are surveying design professionals in practice and academe about methods they use and teach.

Questions to Participants

1. Please define structural design theory and methodology (as you understand it).
Please respond to this question prior to reading the others.
2. After reviewing the table and definitions below, please comment on our definition of structural design theory and methodology.
3. Do *you* teach or practice a particular or range of structural design theory(ies) and methodology(ies) (according to our definitions)? For educators, are these theories incorporated in your design curriculum or capstone project? For practitioners, how do you teach design process to new hires or communicate methodology with clients or members of other disciplines?
4. Are you aware of a structural design methodology or theory that is prevalent, successful, or documented across the profession? If so, please provide references or contacts.
5. In your opinion, is there value to developing the theory and subsequent industry application of structural engineering design theory(ies) and methodology(ies)?

Figure 17. Questionnaire introduction and questions

Table 15. Questionnaire DTM taxonomy: Experimental-Research Based Methodologies

Category		Exemplary Theory or Methodology	Description	Academic Purpose, Results, and Comments
Experimental Research Based Methodologies	Individual	Protocol Studies • Knowledge Flow Model (Waldron and Waldron 1996) • Activity Episode Accumulate Model (Ullman from (Waldron and Waldron 1996)	Observe individual human actions, throughout a design activity as evidence of an underlying individual process.	To understand the tendencies and influences of an individual designer. Has led to the classification of knowledge based on the realization of design functionality (marketability, manufacturability, etc.), classification of knowledge on content (i.e., generic vs. specific vs. info about the knowledge.), and classification of knowledge based on where it is stored in the process (mind or external.)
		Cognitive Studies	Define and test a set of underlying steps and processes that constitute the individual design process.	To develop computer tools to support the individual designer during aspects of design.
	Team	Group Protocol Studies • Design Decision Framework (Krishnan and Ulrich 2001)	Observe group interactions throughout the course of a design project, as evidence of the team design process.	To dissect real design outcomes to understand the processes and dynamics of successful projects. In the case of the decision framework, the purpose is to develop a generic set of questions that must be resolved in all product or project design deliveries.
		Behavior Dynamics Studies • Virtual Design Team (Jin and Levitt 1996)	Define and test a set of underlying steps or interactions through case studies that constitute the team design process.	To develop support methods and tools to facilitate team interaction during design. In the case of VDT, the purpose is understanding designer's response to information queries.

Table 16. Questionnaire DTM taxonomy: Theoretical-Research Based Methodologies

Category		Exemplary Theory or Methodology	Description	Academic Purpose, Results, and Comments
Theoretical Research Based Methodologies: Prescriptive	Process View-Point	• DSM (Steward 1981) • Theory of Technical Systems (Hubka and Eder 1996) • Flow in TFV Theory (Koskela 2000)	To develop, test, and evaluate theoretical constructs of the design process.	To develop formal theories governing design processes or design artifact attributes in the absence of observational data. The purpose of these theories is to develop an idealized process or attribute construct and to then test the validity of these theories through case-study of baseline and "modified" production systems.
	Attribute View-Point	• Axiomatic Method (Suh 1990) • Robust Design (Taguchi from (Clausing 1994) • World Class Concurrent Engineering (Clausing 1994) • Quality Function Deployment (Clausing and Pugh 1991) • Set Based Design (Ward et al. 1995) • Total Design (Pugh 1991) • Value in TFV Theory (Koskela 2000)	Theory based on the attributes an artifact ought to have.	To develop computer tools to support the individual designer during aspects of design.

Table 17. Summary of questionnaire responder experience

Respondent Name	Most Recent Title/ Employer	Years of Practice	Education	Noteworthy Accomplishments
Ben Maxwell SE# 4557	Project Engineer/ LLNL	13 years	BS Civil Engineering- California Polytechnic State University, San Luis Obispo MS Structural Engineering Mechanics and Materials- University of California, Berkeley	Structural Engineer: UC Berkeley CITRIS Building, CSU East Bay Student Services Bldg., UC Silver Laboratory Retrofit, Cal Poly Engineering III, 201 Post St. Seismic Retrofit, San Francisco
Derek Westphal SE# 4663	Project Engineer/ LLNL	13 years	BS Civil Engineering- University of Southern California MS Structural Engineer Mechanics and Materials- University of California, Berkeley	Structural Engineer: San Francisco Intl. Airport BART Extension, UCSF Campus Community Center, San Francisco Jewish Community Center, STEEL TIPS article on base-plates.
Bret Lizundia SE# 3950	Principal/ Rutherford & Chekene Engineers	20 years	BS Civil Engineering- Stanford University MS Structural Engineering- Stanford University	Structural Engineer: New DeYoung Museum San Francisco, Frank Lloyd Wright's Hanna House Retrofit, Genentech Hall at UCSF Mission Bay, Li Ka-Shing Center for Biomedical and Health Sciences at UC Berkeley
Dr. Dave Coats CE# 22929	Division Leader/ LLNL	31 years	BS Civil Engineering PhD Structural Engineering-University of California, Davis	15 years LLNL Division Leader Design and Construction Contributor: DOE Standard 1020 Seismic Recommendations for Nuclear Facilities.
Dr. Alice Agogino ME# 18519	Professor/ UC Berkeley	24 years of combined teaching and practice	BS Mechanical Eng.- Univ. of New Mexico MS Mechanical Engineering- University of California, Berkeley PhD Eng.-Economic Systems- Stanford University	Member National Academy of Engineering, Fellow of ASME, Director Berkeley Expert Systems Technology, Industry experience at Dow Chemical, GE, and SRI International.
Mark Jokerst SE# 3394	Principal/ Forell/Elsesser Engineers	26 years	BS Civil Engineering- California Polytechnic State University, San Luis Obispo	Structural Engineer: Pacific Gas &Elec. Retrofit Headquarters Building, San Francisco, State Court of Appeals Retrofit, San Francisco, State Office Building, San Francisco, San Francisco Museum of Modern Art, Author: 1991 UBC Seismic Regulations

3.5 COLLECTED DATA (RESPONSES)

This section presents responses to the questionnaire. It organizes responses by question, rather than by respondent.

3.5.1 RESPONDENTS' DEFINITIONS OF SE DTM

Question 1: "Please define structural design theory and methodology (as you understand it)."

3.5.1.1 Responses to Question 1

"I would say that I have no formal education or training in this approach and would have defined structural design theory and methodology as the mathematics and physics (e.g., beam theory, buckling, stress and strain relationships, static and dynamic analysis, elasticity theory, etc.) that underlie the design requirements of typical building codes" (P^2SL 2007, Coats).

"Bottom line: limit stress, strain, and deflection to code-mandated values. Other than that it's the Wild West on how you get there" (P^2SL 2007, Maxwell).

"I've never heard of this term (DTM). Wait, in Cal Poly we had a class, I think EDES-302 it was, where we used all kinds of matrices and charts to evaluate designs. But this was an architectural class, not structural design. Beyond that I think right now the approach is for the most part creative and intuitive, that is we arrive at an approach mostly by gut feel for what is given all the parameters. We would make lists of goals, requirements, and constraints. Initial goals could have more sway than other more seemingly rational criteria. The weighting of all parameters is very subjective: it is a little dance both within the structural office and with the client/design team. Everyone arrives with an agenda. Rational evaluation of criteria can be seen as an impediment to one's agenda. Making everyone's 'agenda transparent' or 'on the table for discussion' may generate a non-response" (P^2SL 2007, Jokerst).

"In general, I have had no formal training in design theory either while in college or since I have been at Rutherford and Chekene. Stanford had product design classes that had a good reputation, but I didn't take any. I suspect this would be true of the vast majority of structural engineers. The analogies I tend to sprinkle in conversations with my project engineers include: 1) Structural design is spiral. You make a start at something based on engineering judgment, you do some analysis that makes you rethink it, and you get a little closer to the best answer. Good engineers don't spiral as long. 2) Identify tasks and what it takes to complete them. 3) Decision lists. On some jobs, particularly fast track jobs, I send other members of the design team lists of decisions or tasks I need from them by when and why. Sometimes this works, sometimes it doesn't. It depends on the architect's willingness to listen. 4) Think big, then small" (P^2SL 2007, Lizundia).

"Basically there are three steps to the process, gather the information necessary to design the widget, design the widget, and check the widget meets as many objectives as possible. Often there is missing [data] or unknown parameters, so the designer must assume, or seek advice from someone with more experience. This (selection of parameters) is very important because the validation that a design meets an objective only gains accuracy as the design finalizes but it is usually too late to make changes because of fees, schedule, or client needs" (P^2SL 2007, Westphal).

3.5.1.2 Summary of Responses to Question 1

Design theory, as understood by structural engineers, is typically centered on the application of mathematics and physics laws to solve engineering problems. This is very similar to the definition of engineering as the application of a certain body of knowledge in the creation of structures (Peters and Hopkins 1996).

Design leadership and control of the "project design process" is most often held by the architect. Efforts to communicate consultant needs or to establish a hierarchy of design objectives may be fruitless because of competing agendas within the design team. Alignment of overall project objectives with user values is a challenging and often irrational proposition. This challenge stems not only from competing team objectives, but also from the difficultly of cultivating a shared understanding between the design and construction team about the impact of sub-consultant designs on overall project objectives. Shared understanding can be difficult to develop in a project team because people join the team at different times, so everyone has a different understanding of what has already transpired on the project. Additionally, project complexity can impede a shared understanding. Each team member generates information throughout the course of the project but does not necessarily know what information to share with their team members. Moreover, many project teams do not document alternatives considered and final design decisions, so even if new team members wanted to understand prior decisions, they would not be able to find this information. Further, many project teams do not document their project standards, so new project team members must learn the processes as well as prior decisions. (Chapter 7 expands on the need to document design decisions and project-specific standards to facilitate shared understanding amongst the project team).Finally, contracts are structured to promote a 'divide and conquer' approach, where each sub-consultant optimizes locally. The current system does not provide incentives for collaboration, nor does it require they collaborate, so many sub-consultants choose to optimize locally. Local optimization of sub-consultant practice rarely coincides with the global optimum for the project, so project value for the end user typically suffers.

Design theories are not a part of most structural engineering curricula. Where taught at Universities, these classes tend to be offered as architectural, mechanical engineering, or new product development methodologies. Structural engineers view DTMs as informal processes, handed down through discussions and impromptu lessons from experienced project engineers to team participants. This process involves the framing of problem objectives, determining assumptions, and constraints, analysis of the stated problem, and verification of the results. The solution is often obtained by successive iteration, beginning with broad or high level components and concluding with final details. Experience, intuition, and judgment play key roles in how structural engineers make assumptions and explore the design space as well as the quality of their results.

3.5.2 COMMENTS ON GENERAL TAXONOMY

Question 2: "After reviewing the table and definitions below, please comment on our definition of structural design theory and methodology."

3.5.2.1 Responses to Question 2

"The approach and studies that are outlined in Table 1 [Table 15 and Table 16] appear to be a logical way to understand how individuals and groups currently implement the design process, and where improvements can be made" (P^2SL 2007, Coats).

"I think studying team interactions, especially with consulting peers (architectural, electrical, civil, etc.) would be of great benefit" (P^2SL 2007, Maxwell).

"Individual research and team research appear totally different than prescriptive methodologies" (P^2SL 2007, Lizundia).

"I have never heard of these types of research within a structural design firm" (P^2SL 2007, Westphal).

3.5.2.2 Summary of Responses to Question 2

The responders were able to identify with the framework presented in the table; however they had no previous education on the topics. Several recognized the benefit of research and theory development in the area of team interaction as beneficial and quite separate from prescriptive theory development.

3.5.3 PERSONAL EXPERIENCE WITH SE DTM PRACTICE AND EDUCATION

Question 3: "Do *you* teach or practice a particular or range of structural design theory(ies) and methodology(ies) (according to our definitions)? For educators, are these theories incorporated in your design curriculum or capstone project? For practitioners, how do you teach design process to new hires or communicate methodology with clients or members of other disciplines?"

3.5.3.1 Responses to Question 3

"As a practitioner, we typically taught the design process to new hires by providing them with a mentor to oversee their work and explain how the process worked at the Laboratory" (P^2SL 2007, Coats).

"My theory is to start with big broad strokes and work my way down to the details" (P^2SL 2007, Maxwell).

"No, we have had project management classes in the past on budgeting, detailing, sheet layout, construction administration, etc., but the philosophical process of design was not the focus" (P^2SL 2007, Lizundia).

"No. I would teach it the way I learned it. Simply allow a new hire to start with simple design tasks and grow into larger design tasks without formally explaining a methodology" (P^2SL 2007, Westphal).

3.5.3.2 Summary of Responses to Question 3

The responders described structural engineering DTMs as informal processes developed through experience and informal office training. When formalized as higher learning education or in office training, emphasis is typically placed on conventional "transformational" planning techniques such as cost loaded WBS planning, CPM scheduling, and drawing production planning. Practitioners commonly described a broad initial approach to framing the problem followed by successive iterations narrowing the solution, thereby "spiraling" through the design space to reach the final design. When design process training is provided in offices, it is focused on engineering algorithms rather than an overall team design processes.

3.5.4 Knowledge of Current Industry-wide DTMs

Question 4: "Are you aware of a structural design methodology or theory that is prevalent, successful, or documented across the profession? If so, please provide references or contacts."

3.5.4.1 Responses to Question 4

"No" (P^2SL 2007, Maxwell and Others).

"I am only aware of the 'caveman' mentality. I call it the caveman because it is a brute force method where you learn through experience. You basically have to learn how to make decisions that will have less impact on the other parts of design" (P^2SL 2007, Westphal).

3.5.4.2 Summary of Responses to Question 4

Responses to question 4 reinforced the notion described in section 3 regarding the void in practice of formal DTMs.

3.5.5 PERCEIVED VALUE AND BENEFIT OF SUBSEQUENT STUDY

Question 5: "In your opinion, is there value to developing the theory and subsequent industry application of structural engineering design theory(ies) and methodology(ies)?"

3.5.5.1 Responses to Question 5

"I think that is where 'design theory' ought to be heading. How groups of people work efficiently and creatively toward a common goal" (P^2SL 2007, Jokerst).

"If we switch the conversation away from how we choose an idea to how we develop an idea, then I'm getting excited" (P^2SL 2007, Jokerst).

"But I do think that there is plenty of room on integrating good concurrent engineering and design process" (P^2SL 2007, Agogino).

“I think that there is a need for a uniform design approach, but it needs be one that realizes the constraints imposed on consultants, particularly the need to be flexible in business practices to suit an array of different clients” (P^2SL 2007, Maxwell).

“It would have to be practical, example based, and directly relevant to the practice of consulting structural engineering” (P^2SL 2007, Lizundia).

“Only if it makes my job easier AND keeps me from becoming more of a commodity” (P^2SL 2007, Westphal).

“Particular to the structural world, I think studying team interactions, especially with consulting peers would be a great benefit” (P^2SL 2007, Maxwell).

3.5.5.2 Summary of Responses to Question 5

Individual practitioners are quite aware of the need for the development of design theory. This includes the interaction of design teams as well as the development of the design product. Practitioners identify the need to study entire project production system teams in an effort to optimize the performance of the project as a whole. This team theory represents a recent departure for theorists who have focused on individual design theory prior to the early 1990s. The researchers propose concurrent engineering, set-based methodologies, and enhanced collaboration as DTMs with future applicability.

3.6 SYNTHESIS

The primary findings are:

- Structural engineers receive little or no formal training in DTM in school or in practice. The limited expertise passed down informally in practice promotes point-to-point design methods with multiple iterations.
- Structural engineers are generally interested in exploring new team oriented design processes provided they are simple and cost effective.
- Structural engineers are currently frustrated by the lack of demonstrated leadership on AEC projects. Project process planning in most cases is limited to sending letters indicating "drop dead dates" for information with associated cost penalties.
- Structural engineers acknowledge the need for value alignment across the production system. A shift is required away from viewing engineering services as a commodity. Engineers would prefer a pay-for-performance arrangement where exemplary service is rewarded with higher fees (Tuholski et al. 2009). A major impediment to this fee structure is relating value delivered to overall project savings. Poor trade-offs between conflicting values are major impediments to project success. Engineers also describe the poor translation of user needs into coherent and understandable criteria as major reasons to owner dissatisfaction with design delivery results.
- Practitioners view with skepticism the suggested transplantation of strategies from Toyota or other manufacturing sector companies. This is primarily because of the

apparent dissimilarity between the repetitive nature of car manufacturing versus the temporary nature of project production systems.

- A language barrier currently exists between academic description of theory and application in practice. This barrier inhibits the comparative discussion of management methodologies.
- It is generally perceived that designers can play a significant leadership role in production system optimization if the tools implemented are simple to understand and require little overhead.

3.7 DEFICIENCIES FROM THE TFV PERSPECTIVE

3.7.1 DEFICIENCIES OF CURRENT PRACTICE: LIMITED VALUE

Practitioners who participated in this questionnaire research are not the only ones who identified major design theory deficiencies in current practice. Mar (2005) identifies the poor state of current practice by describing three limiting characteristics including (1) upward creeping budgets, (2) poor coordination, and (3) suboptimal design. His report to the Lean Construction Institute's 'Lean Design Forum' identifies difficulties with the expression and understanding of value as a major hurdle to success. He states that owners often do not fully understand the value characteristics or relative weighting of values on a project. A direct result of this deficiency is the inability of the project team to execute project decisions based on a set of values that is aligned with the target goals of the project.

Value delivery in the design process has applications beyond optimizing the functionality of the product or building. Value from the owner's perspective can be realized through building "design for X" initiatives such as design for sustainability, design for future programmatic flexibility, or design for ease of demolition. Design of realization processes, including supply chain and logistics design, construction methods design, commissioning planning, and demolition design, also helps generate value.

Practitioners who answered the questionnaire reinforced this sentiment by expressing frustrations in meeting the demands of clients. With regard to understanding owner needs on projects, Jokerst (P^2SL 2007) states,

> Beyond that I think right now the approach is for the most part creative and intuitive, that is we arrive at an approach mostly by gut feel for what is right given all the parameters. Oh, you have to know all the parameters first. We would make lists of goals and requirements, constraints. Initial goals could have more sway than seemingly more rational criteria. The weighting of all parameters is very subjective; it is a little dance both within the structural office and with the client/design team. Everyone arrives with an agenda. Rational evaluation of criteria can be seen as an impediment to ones agenda.

This perspective highlights deficiencies with understanding the value perspective of the owner and experience in encountering conflicting agendas. The statement also implies that there are multiple value perspectives, those of the owner and those of the project production system participants. Disparate value sets impede project execution success if they compete or conflict. Mar (2005) concurs when stating that individual goals are often met at the expense of overall project goals.

Westphal (P^2SL 2007) reinforces the lack of detailed value information provided by the owner when he states,

> The designer must gather the design objective or criteria (performance requirements, cost limitations, and programmatic use.) Often there is missing or unknown parameters so the designer must assume, or seek advice from someone with more experience.

Without clear value communication, it is impossible for a design team to meet the needs of the owner and align production system participant values accordingly. Thomson et al. (2006) state that a contributing cause to the absence of value consideration in current AEC practice is the lack of value consideration in detailed design tools.

> Existing practices do not facilitate value delivery when solving technical design problems because they are constrained to conceptual stages. They do not provide designers the means of investigating the relationship between their design decisions made during detailed design stages and the value expectations of project stakeholders. Instead, design is focused on fulfilling technical and performance specifications in these later project stages.

Opportunities exist to enhance the understanding of owner value, alignment of values within the production system team, and design tools that identify value as a necessary component to conceptual and detailed design.

3.7.2 DEFICIENCIES OF CURRENT PRACTICE: LIMITED FLOW

The conventional approach to AEC design and construction management is currently devoid of flow consideration. Mar (2005) highlights this deficiency; he states that designs are often developed independently with little understanding of each other's work, that design teams are fractured with little interdisciplinary contact, that it is difficult for anyone to grasp the complete set of possible interactions between the systems, and that potential system synergies are missed. These expressed deficiencies address the relationship between transformational activities and the flow of information between designers and between design activities.

3.7.3 VOID IN DESIGN THEORY EDUCATION AND TRAINING

Little or no formal training currently exists for structural practitioners in design theory methodologies. This is evident by discussing the topic with well educated practitioners who often cite office mentorship as the primary means by which design methods are taught; Bailey et al.'s (2005) research also observed this means of structural engineering apprenticeship. When questions of design theory education are raised, the typical responses are similar to that of Coats, "*I would say I have had no formal educating or training in this (DTM) approach*" (P^2SL 2007, Coats). The researchers identify an apparent void in DTM related to the performance of teams. Whitney (1990) theorizes that 85% of engineers work in product improvement or reconfiguration areas where they work with large groups on complex integration problems. He then adds that these types of problems do not get much attention from the DTM community.

The void in training is traceable in part to the lack of formal theory developed by AEC practitioners or academics. Where design theory is referenced in civil texts, point-to-point methods are most prevalent. Successive iteration or decomposition are common means by which optimization is achieved (Stephenson and Callander 1974). This void extends beyond the classroom into industry design guides.

3.8 CONCLUSIONS

Structural engineers who responded to this questionnaire report a lack of formal DTM training, both in academe and at the office. Respondents describe DTM in terms of structural design manuals that tend to describe point-to-point methodologies for developing a structurally acceptable design solution. Currently, engineers learn about the design process through mentorship and experience gained on increasingly complex projects rather than through formal training. Mentorship and experience unquestionably improve engineers' insights into the design process, but without education or training in SE DTM, it is difficult to anticipate the impact of changes to the design process. That is, without an understanding of the design process in the context of a DTM framework, it is difficult to decide where the current process lies and what changes to make to improve it.

Research shows the AEC industry is disproportionally focused on the transformation view of design. Questionnaire responses confirm this finding. Received tradition describes structural design as a transformation of owner and architectural requirements into a final structural product (e.g., a building). However, without consideration of flow, the design process has been sub-optimized by each project participant, which can actually cause inefficiencies to develop in the process, including information bottlenecks and excessive hand-offs between participants. Similarly, sub-optimization has led to sub-optimal value delivery. The final product may not incorporate as much value as it could if the design process was more collaborative. Further, lack of value alignment among project participants can cause participant frustration and process delays.

The SEs questioned expressed frustration with the current design process and willingness to try new team-oriented DTMs that support better flow and value alignment in the design process. These engineers postulate a team-oriented DTM would alleviate the language barriers that exist between project participants. However, they expressed skepticism about simply transplanting the principles of the TPS and applying them to the structural engineering community. Rather, SEs support the authors' commitment to developing a structural engineering DTM that works in conjunction with lean tools to improve the design processes used in the AEC sector in light of the responses collected as part of this questionnaire research. Already, the researchers see SEs moving in the direction of collaboration with other project team members. This is particularly evident in structural engineering firms embracing BIM to coordinate work across the project team. Indeed, by championing BIM efforts, the structural engineering firm asserts itself as a project leader as well. SEs who embrace both the technical aspect of BIM as well as the process management side (through DTMs) will be able to provide more value to project owners and project teams alike.

CHAPTER 4. TRANSFORMING A CROSS-FUNCTIONAL DIAGRAM INTO A DESIGN STRUCTURE MATRIX

The cross-functional diagram and Design Structure Matrices presented in this chapter represent a collaborative effort between the author, Dr. Stanislaus Tuholski, and Gernot Hickethier (a visiting graduate student from Universität Karlsruhe), while all three were graduate students at UC Berkeley in the Civil and Environmental Engineering department. They met throughout the summer of 2008 to sharpen their understanding of the design process and model it in the cross-functional diagram and DSMs presented.

4.1 INTRODUCTION

The rebar design and delivery process is a complex system with many interdependencies. Kurtz and Snowden (2003) define a complex system as one where order emerges through the interaction of many entities. Lane and Woodman (2000) describe design and construction as a complex system, as do Tuholski et al. (2009), Maurer and Lindemann (2007), and Ballard et al. (2001), among others. Modeling complex systems can aid in managing them, as models illustrate the order currently in place and allow managers to understand the impacts of process changes.

Chapter 2 introduced two modeling formalisms used in the AEC industry, cross-functional diagrams and the Design Structure Matrix (DSM). Tommelein and Ballard (2005) led a research effort that developed a cross-functional diagram of the rebar design and delivery system (Appendix A). A cross-functional diagram illustrates the dependencies in the design process well; however, iteration is not always obvious in this modeling formalism. In contrast, a DSM clearly illustrates iteration. Then again, a cross-functional diagram may be easier to develop than a DSM is because cross-functional diagrams are spatially representative of the process.

This chapter starts by presenting a cross-functional diagram of the rebar design and delivery system, referred to as the baseline process (Hickethier 2008), and then shows its transformation it into a DSM. The cross-functional diagram used is an abbreviated version of the cross-functional diagram presented in Appendix A. It is transformed into a DSM using the steps described in Chapter 2: (1) decompose a project or system into a process with discrete activities while identifying the required inputs, outputs, and information dependencies, (2) arrange activities sequentially in a square matrix with identical row and column identifiers, and (3) "sequence" activities by means of analysis and manipulation of the assembled matrix. Hickethier (2008) develops alternative processes to improve upon the baseline and he analyzes the alternatives. This chapter focuses on the process of developing a DSM from a cross-functional diagram; discussion of improvements to the baseline process is not within its scope.

This chapter then explores the relationship between DSM and set-based design. DSMs show iteration in a process or system as blocks of activities linked through dependency. As such, they reveal opportunities for application of set-based design and the stakeholders to involve in it. Set-based design can be used to break up iterative blocks in a DSM by releasing dependencies between activities, thereby allowing successive activities to begin earlier than if the dependencies remained. The modeler(s) can analyze the DSM to determine which stakeholders to include in set-based design efforts (e.g., Tuholski and Tommelein 2008; 2009b). Stakeholders whose activities define the iterative block would likely be involved in this effort, but the effort may also include other stakeholders, according to the nature of the dependencies and the activities involved.

4.2 STEP ONE: DECOMPOSE PROJECT OR SYSTEM INTO A PROCESS WITH DISCRETE ACTIVITIES

Decomposing a project or system into a process of discrete activities is the first step in the DSM process. The number of activities corresponds to the size of the matrix, so modelers may opt to combine activities to reduce the total size of the matrix and gain insights into broad trends. For instance, the cross-functional diagram of the rebar design and delivery process presented in Appendix A divides the structural engineer's activities according to submittals to the architect and owner. However, this level of detail (shown in Appendix A) made the DSM cumbersome to read and understand, so the research team combined these drawing activities into a single 'Design Development' activity as shown later.

4.2.1 BASELINE REBAR DESIGN AND DELIVERY PROCESS

Figure 18 is the key with cross-functional diagram symbols. Figure 19 shows the cross-functional diagram of the baseline rebar design and delivery system, consisting of discrete activities. It illustrates the current state of the system. Down the left-hand side of the map are 'lanes' that divide the project according to project stakeholders involved. Time progresses from left to right, so the process is laid out in space on the map corresponding to how it proceeds in time, except in the case of iteration. Iteration consists of a loop through activities; the diagram does not spatially show time spent in these iterative loops. This system begins with Schematic Design (performed by the Structural Engineer) and ends with inspection of installed rebar (shown in the Rebar Placer lane).

Figure 19 represents only a portion of the cross-functional diagram we developed of the total rebar design and delivery system, but it illustrates the linearity of the system imposed by point-based design methodologies, and gives a flavor of the complexity. Although this cross-functional diagram shows only a subset of the stakeholders involved in the rebar design and delivery supply chain, it still captures many of the handoffs in the system.

Because time progresses from left to right, Figure 19 places ‘Schematic Design’ before ‘Design Development’ and links these with an arrow to show that Schematic Design precedes Design Development and information from Schematic Design is necessary for Design Development. Black arrows represent feedforward dependency; i.e., information from one activity is necessary for the succeeding activity to begin. Arrows of different colors represent feedback, which is discussed in Section 4.3.

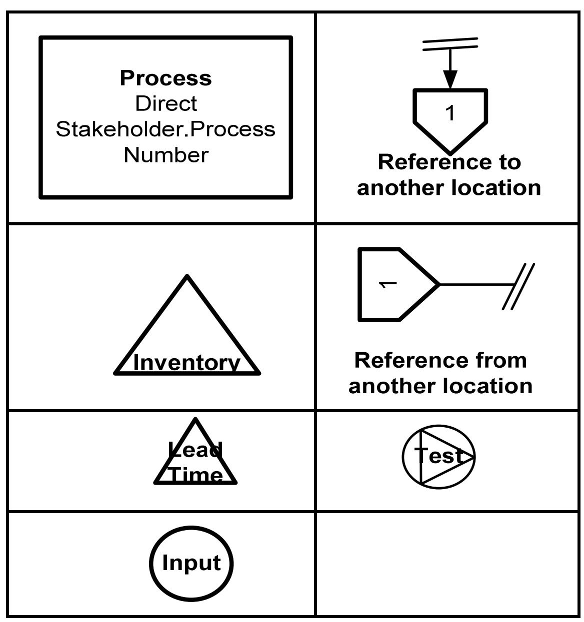


Figure 18. Cross-functional diagram key

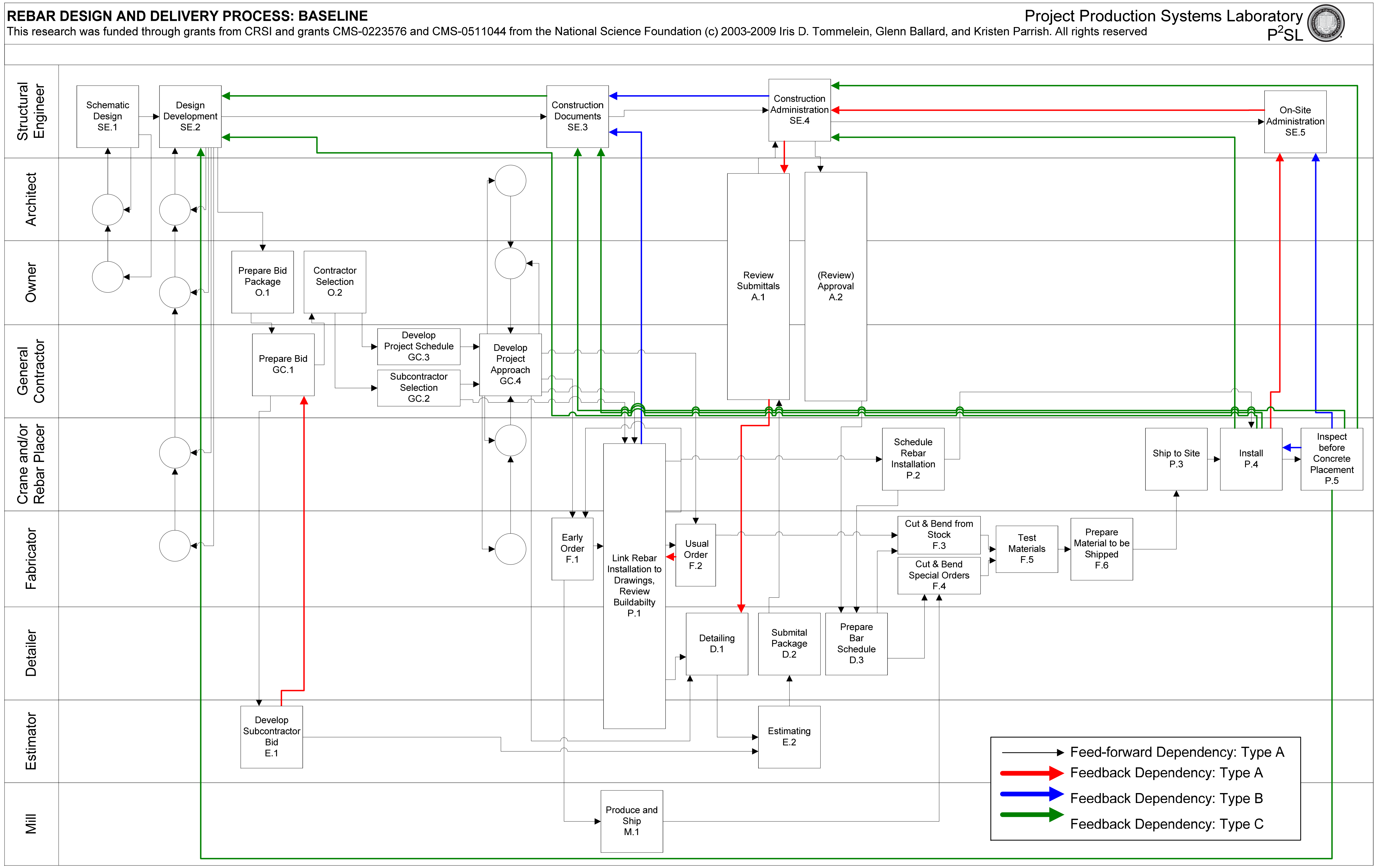


Figure 19. Rebar design and delivery: Baseline cross-functional diagram (figure best viewed in color)

Figure 19 characterizes a design-bid-build process in which contractors and subcontractors bid from the Design Development (DD) drawings. These drawings are to some degree incomplete, i.e., not showing all of the bars or not fully detailed, which may present a problem for rebar bidding, because the DD drawings may. Indeed, in some cases, 'typical' details will not even be provided at that time. Structural engineering firms develop 'typical' details that show rebar configurations for common building areas (e.g., corners, slab-column connections, etc.). These details serve as a point of departure for project-specific rebar details. The estimator ('Estimator') generates a rebar cost estimate (for both labor and material) based on the information provided in the drawings, with some mark-up to account for the incomplete information and reflecting the quality of the drawings in general. The general contractor ('General Contractor') is responsible for completing the project. The general contractor (GC) may self perform some work while managing the subcontractors hired to do the balance of the work onsite. Thus, subcontractor bids are inputs for the project bid the GC submits to the owner. Once the owner ('Owner') awards the prim contract to the selected GC, that GC will award subcontracts. Concurrently, the GC develops a project schedule (the master schedule) that highlights project milestones and their expected completion dates. If the rebar subcontractor recognizes long lead-time items are necessary to complete the work included in the rebar bid, these items may be ordered even before that sub finally joins the project team.

Once the project team is assembled, the owner, the architect, the general contractor, and the rebar subcontractors (represented by the 'Rebar Placer' and 'Fabricator') discuss how the project will fit together ('Develop Project Approach'). Subsequently, the rebar subcontractor (consisting of the ‘Rebar Placer,’ ‘Fabricator,’ ‘Detailer,’ and ‘Estimator’) details the rebar for the project. This activity, ‘Link Rebar Installation to Drawings, Review Buildability,’ involves determining what bars need to be placed and what needs to be fabricated. Once the rebar team internally develops a plan for the project, the various branches of the rebar subcontractor begin their work. The rebar detailer begins to ‘detail the job,’ generating placing drawings that direct the rebar installer how to place rebar in the field (Concrete Reinforcing Steel Institute 2002). These placing drawings are sent to the estimator for costing and the structural engineer for confirmation that they match the designer’s intent. Submissions to the structural engineer may or may not be reviewed by the owner and the architect. The structural engineer checks the placing drawings to ensure rebar is configured to maintain the structural integrity of the element. The placing drawings may or may not be stamped the first time they are submitted. As with submittals, the owner and architect may elect to also review approvals or changes. If approved as conforming to design intent, the detailer generates a bar schedule, listing the number of bars (and tonnage of bars) of a given size, which releases work for the fabricator and placer. Otherwise, the placing drawings must be reworked and re-submitted.

While the detailer is creating placing drawings, the fabricator concurrently begins ordering bars as necessary to maintain the shop inventory (e.g., a three week inventory as some fabricators in the San Francisco Bay Area may maintain) when the project at hand is being fabricated.

After the bar schedule is prepared, fabrication can begin and the rebar placer can develop an installation schedule. Once the installation schedule and bar schedule are complete, the fabrication shop begins to fabricate bars, assemblies, or both. Cutting and bending is split into two activities, 'Cut & Bend from Stock' and 'Cut & Bend Special Orders,' to represent bending done on an automatic stirrup bender—essentially an automatic process—and bending done on more specialized equipment that needs to be programmed and monitored, respectively. If necessary, cut and bent bars are tested before being bundled for shipping.

After it is shipped to site, rebar is placed. Installed rebar that passes inspection gets covered with concrete, otherwise it is either reworked in place (e.g., the placer adds more rebar if the inspector claims the rebar configuration does not satisfy the rebar area requirement) or pulled out (e.g., the inspector claims rebar does not satisfy the spacing requirement). In the case of a failed inspection, the structural engineer, the inspector (an outside agent), the GC, and the rebar subcontractor collaborate to develop an alternative rebar configuration that meets all of the inspector's requirements.

Appendix A details both the role of each supply chain player as well as the rebar design and delivery system.

4.3 STEP TWO: ARRANGE ACTIVITIES IN A SQUARE MATRIX

Figure 20 illustrates the activities of the rebar design and delivery system arranged in a square matrix in Microsoft Excel. Other software programs, e.g., ADePT™ (http://www.adeptmanagement.com/index.html) and LOOMEO (http://www.teseon.com/index.php?lang=en), assist designers in generating and sequencing DSMs. The left-hand side of the matrix lists the activities by number and name (corresponding to the cross-functional diagram shown in Figure 19). The top of the matrix lists them by number only. Figure 19 shows Type A, Type B, and Type C feedback dependencies (as, e.g., ADePT™ uses), corresponding to 100%, 70%, and 30% probability of rework, respectively (Hickethier 2008). These probabilities reflect modeler preference and understanding of the system. Hickethier (2008) suggests selecting trial values for the probability of rework for A, B, and C dependencies and performing sensitivity analysis to verify these values. Figure 20 indicates dependence with a mark, either an 'A,' a 'B,' or a 'C,' which correspond to 'Type A,' 'Type B,' and 'Type C' dependencies, respectively.

Dependency is read across a row. That is, "the activity in the i^{th} row depends on the activity in the j^{th} column." An 'X' below the diagonal indicates feedforward dependency. For example, in the 'GC.1 Prepare Bid' row, the 'X's below the diagonal show 'Prepare Bid' depends on 'SE.1,' 'SE.2,' and 'O.1,' corresponding to Schematic Design, Design Development, and Prepare Bid Package, respectively. That is, 'Prepare Bid' takes information from Schematic Design, Design Development, and Prepare Bid Package as inputs.

An 'A' entry above the diagonal indicates feedback dependency. An 'A' entry below the diagonal indicates feedforward dependency. Reciprocal dependence refers to cases where two activities have both feedback and feedforward dependency. For example, the 'GC.1 Prepare Bid' row and the following row, 'E.1 Develop Subcontractor Bid' illustrate reciprocal dependency. The 'A' above the diagonal in the 'E.1' column indicates feedback dependency between 'GC.1 Prepare Bid' and 'E.1 Develop Subcontractor Bid.' The 'A' below the diagonal in the 'GC.1' column indicates feedforward dependence from 'GC.1 Prepare Bid' to 'E.1 Develop Subcontractor Bid'.

A ‘B’ indicates moderate feedback dependency, or feedback that will occur 70% of the time. For instance, the ‘B’ in ‘P.1’ column of the ‘SE.3 Construction Documents’ row indicates construction documents will be reworked as a result of information from ‘P.1 Link Rebar Installation to Drawings, Review Buildability’ 70% of the time.

A ‘C’ indicates a weak feedback dependency, meaning rework occurs 30% of the time. For example, the ‘C’ in the ‘SE.3’ column of the ‘SE.2 Design Development’ row denotes Design Development is reworked 30% of the time as a result of Construction Documents.

4.4 STEP THREE: SEQUENCE THE REBAR DESIGN AND DELIVERY BASELINE DSM

Sequencing involves analysis and manipulation of the square matrix assembled in Step Two (Figure 20). Analysis identifies iteration blocks in the DSM. Manipulation involves re-sequencing the DSM into a more optimal process.

4.4.1 ANALYSIS OF THE REBAR DESIGN AND DELIVERY BASELINE DSM

Figure 21 illustrates seven iteration blocks in the rebar design and delivery baseline DSM. Block 1 represents the iteration between ‘Link Rebar Installation to Drawings, Review Buildability’ and ‘Design Development.’ Block 2 represents the iteration between the general contractor and the subcontractor in developing a project bid. Block 3 represents the rework of construction documents throughout the construction administration phase. Within this block, three others exist. The first sub-block, Block 4, represents iteration between the fabricator ordering material and the rebar subcontractor linking the rebar installation to the Design Development drawings. The second sub-block, Block 5, represents the placing drawing submission and rework process between the detailer and the architect. The third sub-block, Block 6, also represents the placing drawing submission and rework process. However, this block includes changes from the structural engineer as well as the architect (Block 5 only includes rework due to architect changes). Finally, Block 7 represents rework due to rebar failing inspection.

Hickethier (2008) explains Blocks 1, 2, 3 (which includes blocks 5 and 6), 4, and 7:

> [Block 1]: 'Link Rebar Installation to Drawings' includes the buildability check by the rebar placer, the rebar fabricator, the detailer, and the estimator. Problems with buildability provoke feedback loop 1, because requests for clarification to the structural engineer about buildability may provoke a redesign of the building system. The structural engineer designs the building system in Design Development. The main objective of feedback loop 1 is product design and construction process design. But processing of addenda to the construction project also takes place, because changes in the building system may change the workloads of project participants.

He goes on to explain Block 2:

> To finish his own bid, the general contractor needs a cost estimate from the estimator for the subcontractor's work share. Usually several iterations between [the] general contractor and subcontractor occur to reduce the cost estimate.

He explains Block 3:

> In 'Construction Administration' the structural engineer reviews the building system that he developed himself during 'Construction Documents' and he reviews the placing drawings developed by the detailer. If the structural engineer should find errors in the building system, he has to go back into 'Construction Documents' and modify the building system. If he finds errors in the placing drawings, he sends them back to the detailer or [to the architect, owner, or general contractor for review]. Thus, feedback loop 3 contains detailed engineering of the building.

He explains Block 4:

> The fabricator orders usual material after he, the rebar placer, the detailer, and the estimator linked rebar to installation drawings. If the material they plan to use is not available, they have to rework the links between rebar installation and drawings of the building system.

Baseline Process Original Sequence	SE.1	SE.2	O.1	GC.1	E.1	SE.3	O.2	GC.2	GC.3	GC.4	F.1	P.1	M.1	F.2	D.1	E.2	D.2	SE.4	A.1	A.2	P.2	D.3	F.3	F.4	F.5	F.6	P.3	SE.5	P.4	P.5
SE.1 Schematic Design	■																													
SE.2 Design Development	A	■				C						A																	C	C
O.1 Prepare Bid Package	A	A	■																											
GC.1 Prepare Bid	A	A	A	■	A																									
E.1 Develop Subcontractor Bid		A	A	A	■																									
SE.3 Construction Documents	A	A				■						B							A										C	C
O.2 Contractor Selection				A	A		■																							
GC.2 Subcontractor Selection					A		A	■																						
GC.3 Develop Project Schedule	A	A					A		■																					
GC.4 Develop Project Approach	A	A						A	A	■																				
F.1 Early Order	A	A							A	A	■																			
P.1 Link Rebar Installation to Drawings	A	A					A	A	A	A	A	■		A																
M.1 Produce and Ship											A		■																	
F.2 Usual Order											A	A		■																
D.1 Detailing	A	A				A				A		A			■			A	A											
E.2 Estimating	A	A			A	A									A	■														
D.2 Submittal Package	A	A				A									A	A	■													
A.1 Review Submittals		A				A									A	A	A	■	A											
SE.4 Construction Administration	A	A				A			A						A	A	A	A	■										C	C
A.2 (Review) Approvals		A				A											A	A	A	■										
P.2 Schedule Rebar Installation	A	A							A	A		A									■									
D.3 Prepare Bar Schedule		A								A		A					A			A	A	■								
F.3 Cut & Bend from Stock														A						A		A	■							
F.4 Cut & Bend Special Orders											A		A	A						A		A		■						
F.5 Test Materials																							A	A	■					
F.6 Prepare Material to be Shipped																							A	A	A	■				
P.3 Ship to Site											A		A	A						A	A	A				A	■			
SE.5 On-Site Administration	A	A				A											A	A	A	A	A						A	■	A	B
P.4 Install						A														A	A						A	A	■	A
P.5 Inspect before Concrete Placement		A				A														A					A			A	A	■

Figure 20. Rebar design and delivery: Activities arranged in square matrix, the Baseline DSM

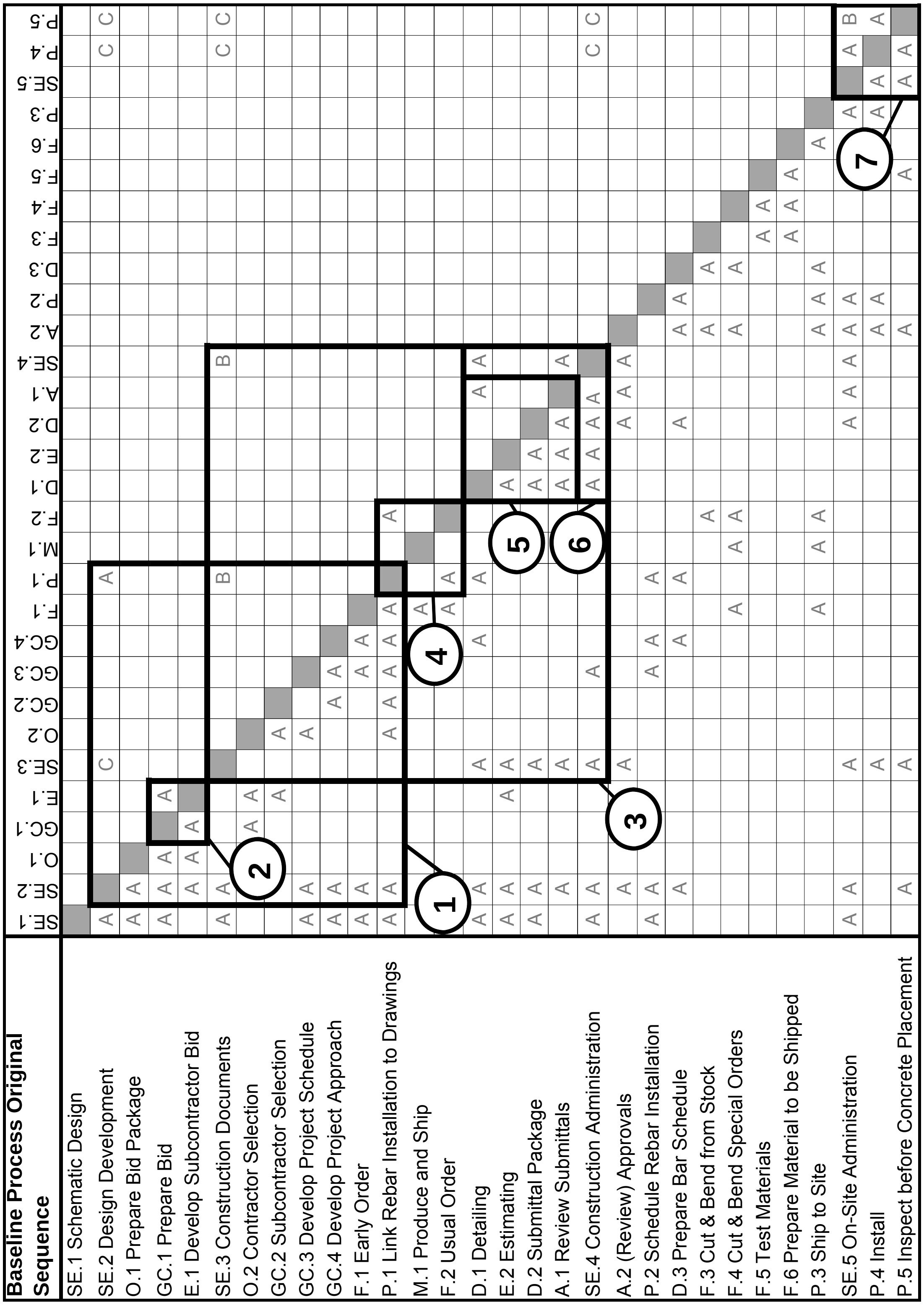


Figure 21. Rebar design and delivery: Baseline DSM highlighting iterative blocks in original sequence

He explains Block 7:

> Variation from the planned process causes rework during the installation phase. Variation can arise from installation and inspection. In both cases Onsite Administration re-organizes the installation process and tries to find a solution on-site in case there are problems with drawings or materials. Usually, problems cause installation rework. Feedback loop 5 contains onsite work.

Figure 21 does not highlight blocks made up of C dependencies because such dependencies are weak, meaning they are less likely to occur. However, if one of these iterative blocks is engaged, the rework may be significant. If placed rebar does not pass inspection, the entire process may need to be repeated. If a new rebar concept is developed, project stakeholders often try to move through the design process quickly to minimize project delays, so despite weak dependency, project managers may want to monitor activities in iterative blocks made of C dependencies. Figure 21 highlights only full iteration blocks. For example, the "block" containing 'SE.3' through 'P.1' (the intersection of Blocks 2 and 3) is not highlighted because there is no mark in the 'SE.3' column of the 'P.1 Link Rebar Installation to Drawings' row. Therefore, Construction Documents may receive input from Link Rebar Installation to Drawings, but Link Rebar Installation to Drawings does not depend on Construction Documents. If the rebar placer, detailer, fabricator, and estimator make suggestions to the structural engineer as a result of 'Link Rebar Installation to Drawings,' they are addressed by the structural engineer during the 'Construction Documents' phase. However, the 'Link Rebar Installation to Drawings' activity depends on drawings produced in 'Design Development,' so the 'Link Rebar Installation to Drawings' activity would not be repeated as a result of the structural engineer's response to the suggestions of the rebar placer, fabricator, detailer, and estimator. Rather, Block 6 would be engaged to address these suggestions.

4.4.2 MANIPULATION OF THE REBAR DESIGN AND DELIVERY BASELINE DSM

Hickethier (2008) explains how the rebar design and delivery baseline DSM was sequenced:

> All DSMs in this case study are sequenced with the 'combined method KU93 enhanced' algorithm. Kusiak (1993) introduced the KU93 algorithm for cluster identification. LOOMEO allows the combined application of the KU93 algorithm with systematic permutation of highly interrelated parts of the matrix; this approach is called the 'combined method'. Algorithms cannot determine an optimal sequence for highly interrelated areas… Systematic permutation through possible sequences can help obtain an optimal sequence of elements. The KU93 algorithm identifies the overlapping clusters; permutation of elements from the overlapping clusters instead of permutation of all elements reduces the computational effort.

Figure 22 shows the sequenced rebar design and delivery baseline DSM. Hickethier (2008) explains its improvement over the Baseline Process:

> Sequencing of the Baseline Process removes negative iteration, and thus reduces uncertainty. In the original process, buildability is reviewed (activity: Link Rebar Installation to Drawings) after the building structure was developed (activity: Construction Documents). Denial of buildability (activity: Link Rebar Installation to Drawings) changes the building system (activity: Design Development) from which the building structure is developed (activity: Construction Documents). This dependency causes the interlocking feedback loops, because 'Link Rebar Installation to Drawings' belongs to feedback loop 1 and 'Construction Documents' belongs to feedback loop 3.
>
> In the KU93 sequenced process, development of the building structure (activity: Construction Documents) takes place after buildability has been assessed (activity: Link rebar installation to drawings). Sequencing eliminates the interlock between detailed engineering (feedback loop 3) and the product design and construction process design (feedback loop 1), because detailed engineering starts after the subcontractor's views were incorporated into the product design. The eliminated interlock resolves the need to change the construction process design, which consists of project schedule development and project approach development, if buildability is denied.

Baseline Process, Sequenced	SE.1	SE.2	O.1	E.1	GC.1	O.2	GC.2	GC.3	GC.4	F.1	P.1	F.2	M.1	P.2	SE.3	D.1	E.2	D.2	A.1	SE.4	A.2	D.3	F.3	F.4	F.5	F.6	P.3	SE.5	P.4	P.5
SE.1 Schematic Design																														
SE.2 Design Development	A										A				C														C	C
O.1 Prepare Bid Package	A	A																												
E.1 Develop Subcontractor Bid		A	A		A																									
GC.1 Prepare Bid	A	A	A	A																										
O.2 Contractor Selection				A	A																									
GC.2 Subcontractor Selection				A		A																								
GC.3 Develop Project Schedule	A	A				A																								
GC.4 Develop Project Approach	A	A					A	A																						
F.1 Early Order	A	A						A	A																					
P.1 Link Rebar Installation to Drawings	A	A				A	A	A	A	A		A																		
F.2 Usual Order										A	A																			
M.1 Produce and Ship										A																				
P.2 Schedule Rebar Installation	A	A						A	A		A																			
SE.3 Construction Documents	A	A									B									B									C	C
D.1 Detailing	A	A							A		A				A				A	A										
E.2 Estimating	A	A		A											A	A														
D.2 Submittal Package	A	A													A	A	A													
A.1 Review Submittals		A													A	A	A	A		A										
SE.4 Construction Administration	A	A						A							A	A	A	A	A										C	C
A.2 (Review) Approvals		A													A			A	A	A										
D.3 Prepare Bar Schedule		A							A		A			A				A			A									
F.3 Cut & Bend from Stock												A									A	A								
F.4 Cut & Bend Special Orders										A		A	A								A	A								
F.5 Test Materials																							A	A						
F.6 Prepare Material to be Shipped																							A	A	A					
P.3 Ship to Site										A		A	A	A							A	A				A				
SE.5 On-Site Administration	A	A												A	A			A	A	A	A						A		B	A
P.4 Install														A	A						A						A	A		A
P.5 Inspect before Concrete Placement		A													A						A				A			A	A	

1 2 3 4 5

Figure 22. Rebar design and delivery: Baseline DSM, sequenced

> The KU93 sequence shows a lot less negative iteration relative to the original sequence, because product design and detailed engineering are not interlocked. The value of the product generated by the process is presumably equal in both processes, because the processes have the same structure. As mentioned in section 4.4, DSM is a tool for modeling of iterative processes, but it does not explicitly model product value. Thus, evaluation of modification of value generation must be interpreted carefully. Case 2 of the evaluation of process structure modification methodology states a positive result of process modification. KU93 sequencing develops a sequence of activities with less uncertainty than the original process sequence while maintaining an equal[ly] value[d] product.

The sequenced process serves as a benchmark process. Project teams may suggest changes to the rebar design and delivery system in attempts to improve it. The effects of these changes would be compared to the sequenced DSM, revealing whether or not they improved the process. An improved process would boast fewer iterative blocks, fewer activities within iterative blocks, or more value-added activities in the process.

4.5 RELATIONSHIP BETWEEN DSM AND SET-BASED DESIGN

Projects with incomplete, but accurate, information, characterized as uncertain projects (Schrader et al. 1993), are good candidates for set-based design (Gil et al. 2008; Pich et al. 2002). Set-based design uses incomplete information to develop a set of design alternatives in accordance with the information available. The detail of these alternatives is aligned with the information available. As more complete information is available, the set of design alternatives is developed with more detail. Thus, rework is avoided. Conversely, point-based design focuses on quickly generating a design, requiring assumptions to be made to supplement the incomplete information. If, later on, the more complete information conflicts with assumptions made, rework may be necessary to reconcile the design with the complete information.

Projects with complete, but inaccurate information—ambiguous projects—are better candidates for iterative strategies similar to point-based design (Terwiesch et al. 2002). Developing sets of design alternatives in ambiguous projects often leads to additional rework, as the sets are developed with incomplete, and often inaccurate, information. Thus, design needs to be reworked not only as more complete information becomes available, but also as information becomes more accurate.

In order to decide whether or not set-based design is an appropriate project management strategy, managers must understand the ambiguity and uncertainty of a project. Schrader et al. (1993) explain uncertainty and ambiguity are a function of the project type and the project team. Terwiesch et al. (2002) suggest using a modified decision tree to determine the ambiguity and uncertainty of a project. Further, they highlight the need to understand the stability of information (i.e., how much will the information change over the course of the project?). They state that set-based design is most successful in projects with stable information.

DSMs highlight iteration and information exchange. Thus, DSMs illustrate opportunities to employ a set-based strategy. DSMs in their original sequence highlight all the iteration "inherent" in a process. The sequenced DSM highlights iteration that cannot be removed through re-sequencing alone. The iterative blocks remaining after sequencing are those that need extra attention from managers (Tuholski 2008). Set-based design can work to reduce the frequency of iteration through these blocks as well as the amount of information being exchanged in successive iterations. Set-based design involves multiple stakeholders earlier in the process than is typical with point-based design, so the iteration between these stakeholders can often go faster (ideally, it would be instantaneous, e.g., in a meeting), as less time is spent correcting assumptions. Also, information shared is based on stakeholders' experience and expertise, rather than assumptions, so it is more accurate. Moreover, information shared in set-based design is usually stable (though it may be incomplete), so it can be incorporated into the set of design alternatives. By sharing stable information early, less information needs to be shared in successive iterations, thus reducing time spent in the iteration block. Finally, early collaboration amongst the stakeholders reduces the likelihood of entering a rework loop, so iteration happening in an iterative block is more likely to be positive.

4.6 SET-BASED DESIGN ANALYSIS OF THE REBAR DESIGN AND DELIVERY SYSTEM

The DSM developed in this chapter highlights negative iteration in the rebar design and delivery system. Sequencing of the baseline DSM removed some of its iterative blocks (Hickethier 2008), but five remain. Remaining iteration blocks relate to buildability review (Block 1), the bid process (Block 2), material ordering and detailing (Block 3), review of placing drawings (Block 4), and failure to pass inspection (Block 5). The author next analyzes each of these blocks and determines whether or not a set-based design strategy could release the dependencies that form the iterative blocks.

Block 1 illustrates iteration due to buildability review. The buildability review is an uncertain process, which suggests a set-based design strategy could improve it. Specifically, a set-based design strategy could release the Type A dependency between 'SE.2 Design Development' and 'P.1 Link Rebar Installation to Drawings.' The rebar placer and the structural engineer could develop the drawings together, allowing the rebar placer to help develop buildable details for the project. The project team may consider including the rebar estimator, detailer, and fabricator in the set-based buildability review, as they may help the structural engineer and placer develop details that take advantage of the unique capabilities of the fabricator and minimize constructability issues. At a minimum, the structural engineer could share incomplete, but accurate, information to allow other activities to progress. For instance, the structural engineer could specify the required rebar area and a range of bar sizes based on ACI spacing requirements. This would allow the owner to prepare a bid package and subsequently release bidding work to the general contractor and rebar estimator.

Block 2 (Figure 22) illustrates iteration in the bid process, an ambiguous process that requires complete information. Preparing a bid requires complete information that is as accurate as possible. However, the need for complete information is greater than the need for accurate information, as bids can contain some contingency. Thus, set-based design efforts would likely *not* substantially improve the bid process. That is, it may reduce the time spent in this iterative block, but it may not remove the dependency between the activities.

Block 3 (Figure 22) illustrates iteration between the rebar placer and fabricator required to place a material order based on the drawings. This process is uncertain, as the fabricator could make an order with incomplete, but accurate, information. Thus, a set-based design strategy could improve the process. The placer and fabricator could review the drawings together and agree on a material order that ensures necessary rebar will be available for placing. Also, the fabricator can inform the placer about any material shortages, so the placer can suggest changes to the rebar design to accommodate the material constraints.

Block 4 (Figure 22) illustrates iteration in the placing drawing review process. This process is characterized as uncertain, so a set-based design strategy could improve it. The structural engineer, the detailer, and the architect could collaborate to develop placing drawings that satisfied each party. They could share the incomplete information they each had to define and explore the design space. For instance, the detailer could submit placing drawings in smaller batches to release work for the estimator. The set-based design strategy could include the estimator to concurrently develop cost estimates. This process may also benefit from co-locating the structural engineer, the detailer, the architect, and the estimator, which may reduce the wait time between submission ('D.2 Submittal Package') and review ('A.1 Review Submittals' and 'SE.4 Construction Administration').

Block 5 illustrates iteration resulting from rebar inspection. This is an ambiguous process, as installation must be complete before inspection takes place. Thus, a set-based design strategy would likely not make significant improvements to the process.

Modelers can analyze iterative blocks in DSMs to determine whether they illustrate uncertain or ambiguous processes. As was illustrated, uncertain processes benefit from application of a set-based design strategy, as sharing incomplete, but accurate, information can release dependencies, and thus release work for successive activities. By contrast, ambiguous processes require complete information, even if inaccurate (e.g., rebar inspection requires rebar installation be complete), so these processes may not benefit from application of a set-based strategy. That is, sharing incomplete information may not release dependencies, so the set-based design strategy may not yield significant process improvements.

4.7 CONCLUSIONS

This chapter describes how to transform a cross-functional diagram into a DSM. It transformed the cross-functional diagram illustrating the baseline rebar design and delivery system into a DSM that showed the original sequence of activities; it was sequenced to improve the process by reducing the size of iterative blocks. A cross-functional diagram can be transformed into a DSM by placing marks in the matrix that correspond to arrows in the cross-functional diagram. The author followed a DSM formalism that divides feedback into A, B, and C dependency, according to likelihood of occurrence. The DSM software ADePT™ uses this formalism, though other DSM software (e.g., LOOMEO) may use another formalism for classifying dependencies.

This chapter presented a diagram that highlights the many participants involved in the rebar supply chain, each with their own competencies and values. Currently, many of these participants “act in a vacuum” and may have minimal communication with each other. In some cases this makes sense, as the transactional relationship is one of a provider and a buyer exchanging a product (e.g., the relationship between a scrap dealer and a rolling mill). However, in most cases, supply chain participants have a provider and a buyer relationship exchanging a service, as is the case of the rebar fabricator and the structural engineer. As the rebar design process progresses, the rebar fabricator is a customer (e.g., of the structural engineer) and then a service provider (e.g., furnishing the structural engineer with placing drawings). The diagram allows each stakeholder to *see* their customers and product or service providers at a given point in the design process, providing an opportunity for collaboration that stakeholders may not take advantage of. A set-based methodology for rebar design offers a means of communication between parties who may not converse in the current state; furthermore, a set-based methodology allows for downstream stakeholder values to be considered during design.

The current state of the rebar design and delivery system involves iteration between the architect, the structural engineer, the rebar detailer, and the rebar fabricator (see Appendix A). Some of this iteration is positive (Ballard 2000c); it sparks creativity in structural design, fabrication, and construction means and methods. However, much of the iteration is negative (Ballard 2000c); it generates waste in the design and construction process. Exposing iteration offers stakeholders an opportunity to find negative iteration in the process, and develop process innovations and improvements to reduce it.

Iteration in the process became visually obvious when the cross-functional diagram was transformed into a DSM, because iteration was shown in blocks rather than with closed circuits of arrows. The author and her colleagues analyzed iterative blocks to determine what information was shared within them. Then, they sequenced the DSM to facilitate earlier involvement of and collaboration between project stakeholders. The sequenced DSM illustrates areas where set-based design may be most effective—areas where information is stable but incomplete. Therefore, use of DSMs can guide project managers about where to employ a set-based design strategy.

CHAPTER 5. SELECTING REBAR FOR A BEAM-COLUMN JOINT USING CHOOSING BY ADVANTAGES

5.1 INTRODUCTION

Beam-column joints may require extra attention in the process of designing a reinforced concrete structure, as they tend to be congested (i.e., rebar in the joint is very dense). As such, choosing rebar for beams and columns intersecting at a joint can be a challenging task. Structural engineers tend to design beam and column reinforcement individually and then verify compatibility within the joint. The American Concrete Institute's (ACI) code, ACI 318, mandates compatibility checks, including development length for the beam rebar, area ratio of rebar in the joint, and rebar diameter requirements for beams and columns. However, ACI does not explicitly impose constructability requirements, so despite meeting ACI requirements, joints may be difficult to build. While a design may be satisfactory to a structural engineer, it may be far from satisfactory for the rebar fabricator and the placer. Using Choosing By Advantages (CBA), the latter two project stakeholders can offer their assessment of alternative designs side-by-side with the structural engineer's. This chapter presents the canonical example of reinforcing a beam-column joint in a reinforced concrete frame. The example walks the reader through the Tabular Method of CBA for selecting a rebar configuration for this joint.

5.2 DEVELOPING A SET OF BEAM-COLUMN JOINT ALTERNATIVES

CBA is a decision-making system that includes methods for virtually all types of decisions, from very simple to very complex. For moderately complex decisions, the CBA process consists of five phases: (1) the Stage-Setting Phase, (2) the Innovation Phase, (3) the Decisionmaking Phase, (4) the Reconsideration Phase, and (5) the

Implementation Phase. The Tabular Method is for moderately complex decisions. The third phase is the primary subject of Suhr's 1999 book, *The Choosing By Advantages Decisionmaking System.* In the Tabular Method, Phase 3 comprises four steps: (1) Summarize the attributes of each alternative, (2) Determine the advantages of each alternative, (3) Assign a degree of importance to each advantage, and (4) Choose the alternative with the greatest total importance of advantages.

Figure 23 shows a reinforced concrete frame. It labels Beam B and Column C, and lists the required area of rebar for each member. To begin, the structural engineer applies a "divide and conquer" methodology, designing the beams and columns separately, to determine sets of possible beams and columns. This example explores two of the reinforced concrete frame design spaces: one for the beam and one for the column. Other dimensions of the design space (not explored here) include beam and column dimensions, concrete strength, aggregate size, and others.

During the Innovation Phase of the CBA process, 'must' criteria rule out the unacceptable alternatives. The ACI code imposes 'must' criteria, i.e., criteria each and every alternative must meet. If a design team designs a structure that does not meet code requirements, they must negotiate another means of proving structural integrity to the permitting agency. To develop a set of design alternatives for the beam based on the ACI 318 structural concrete code (ACI 2005), the engineer calculates the minimum area of required reinforcement, tension steel, A_s, located at the top of the beam, and compression steel, A_s', located at the bottom of the beam, necessary to achieve the required beam flexural strength. In this example, the beam is 18 in by 24 in, which requires $A_s > 3.00$ in^2 and $A_s' > 1.80$ in^2. Similarly, the structural engineer calculates minimum required steel area for the column and determines it to be $A_s > 9.50\ in^2$. ACI 318 also imposes an upper bound on A_s and A_s'; it limits the rebar reinforcement ratio (a ratio of rebar area to concrete area for a given cross section) to a maximum of 0.025 in order to achieve ductile section behavior.

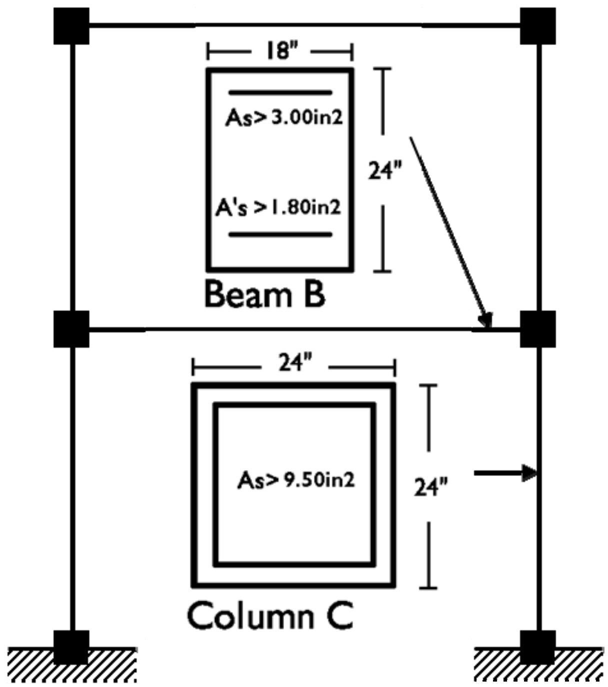


Figure 23. Canonical Example of Reinforced Concrete Frame with Beam B and Column C (Figure 3 in Parrish et al. 2007)

Following these calculations, the team must define sets of beam and column reinforcement alternatives. The set of possible designs is large in this case as many reinforcement configurations meet the rebar area requirement. A computer could enumerate all elements in the set of design alternatives that completely defines the feasible design space. Figure 24 shows a representative sampling of the beam design space before applying 'must' criteria, including beams representing various bar sizes, as well as various configurations (i.e., one or two layers of rebar in the top of the beam). Likewise, Figure 25 shows different bar sizes as column reinforcement alternatives in the design space. However, for brevity, these figures do not show every possible reinforcement scheme.

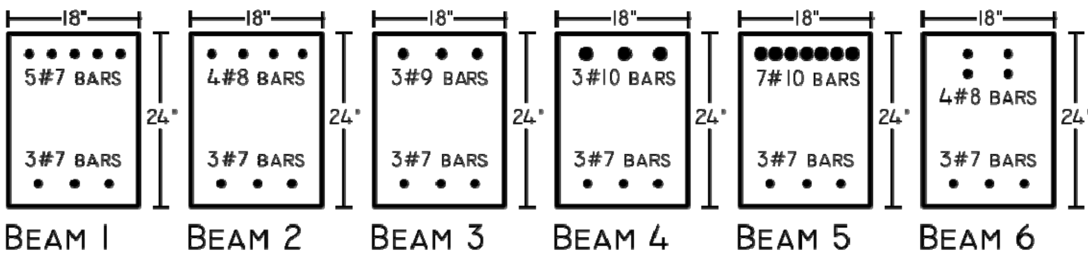


Figure 24. Sampling of the design space for Beam B (Figure 4 in Parrish et al. 2007)

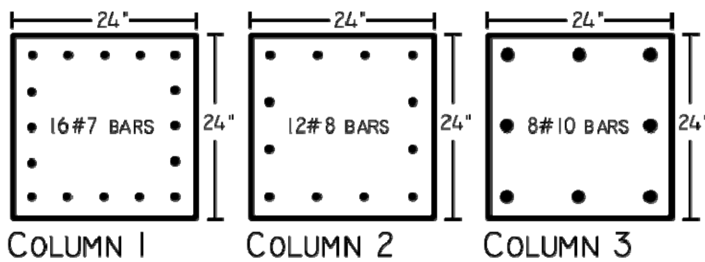


Figure 25. Sampling of the design space for Column C (Figure 5 in Parrish et al. 2007)

By applying 'must' criteria, design teams can narrow the set of reinforcement alternatives for the beam and the column. ACI 352 states bars entering a joint must have diameters less than 1/20 the height of the beam or column framing into it (ACI 2002). Both the beam and the column in this example have a 24-inch height, which means bar diameters must be less than 1.20 inches. This eliminates beams and columns reinforced with #10 (diameter = 1.27 inch), #11 (diameter = 1.41 inch), #14 (diameter = 1.69 inch), and #18 (diameter = 2.26 inch) bars from consideration. This eliminates Beam 4, Beam 5 (Figure 24), and Column 3 (Figure 25) from further consideration. Further, ACI 318 requires spacing between beam bars be at least 1 inch and spacing between column bars be at least 1.5 inches (ACI 2005). This eliminates beams reinforced with #3 or #4 bars on the top and columns reinforced with #3 or #4 bars from the set of alternatives. ACI 352's clear spacing requirements between the beam and column reinforcement eliminate Beam 1. If the design team decides a 'must' criteria may be, "All rebar at a given location (top of beam, bottom of beam, or column) must be the same size," the set of reinforcement alternatives is reduced to 30 beams and five columns, totaling 150 alternatives. Table 18 lists the beam reinforcement alternatives, and Table 19 lists the column reinforcement alternatives. Note the 'No. of bars' column states the minimum number of bars necessary to meet the area requirements. The design team could decide to use more bars, though these tables do not list these alternatives.

Now, the team can apply want-criteria to further reduce the set. For instance, a beam reinforced with many #5 bars may satisfy ACI requirements, but so many pieces that it is not advantageous relative to other alternatives with respect to constructability. Similarly, the column reinforced with #5 bars has so many pieces to not be advantageous relative to other alternatives with respect to constructability. Although ACI 318 requires 10 #9 bars for column reinforcement, this leads to an asymmetric reinforcement scheme (not all sides of the column would have the same number of bars), so a structural engineer may opt to use 12 #10 bars instead. For the same reason, a structural engineer may prefer to use 12 #8 bars for column reinforcement and justify not meeting the area requirement (see 5.4.1). Thus, the design team can effectively eliminate a column reinforced with #9 bars from the set of alternatives, because it would be heavier than the alternative reinforced with #8 bars but have the same number of pieces, so it would not be advantageous with respect to constructability.

Table 18. Set of beam reinforcement alternatives

Top of Beam			Bottom of Beam			Total
Bar Size	No. of bars	Area (in^2)	Bar Size	No. of bars	Area (in^2)	Area (in^2)
#5	10	3.10	#4	9	1.80	4.90
			#5	6	1.86	4.96
			#6	5	2.20	5.30
			#7	3	1.80	4.90
			#8	3	2.37	5.47
			#9	2	2.00	5.10
#6	7	3.08	#4	9	1.80	4.88
			#5	6	1.86	4.94
			#6	5	2.20	5.28
			#7	3	1.80	4.88
			#8	3	2.37	5.45
			#9	2	2.00	5.08
#7	5	3.00	#4	9	1.80	4.80
			#5	6	1.86	4.86
			#6	5	2.20	5.20
			#7	3	1.80	4.80
			#8	3	2.37	5.37
			#9	2	2.00	5.00
#8	4	3.16	#4	9	1.80	4.96
			#5	6	1.86	5.02
			#6	5	2.20	5.36
			#7	3	1.80	4.96
			#8	3	2.37	5.53
			#9	2	2.00	5.16
#9	3	3.00	#4	9	1.80	4.80
			#5	6	1.86	4.86
			#6	5	2.20	5.20
			#7	3	1.80	4.80
			#8	3	2.37	5.37
			#9	2	2.00	5.00

Table 19. Set of column reinforcement alternatives

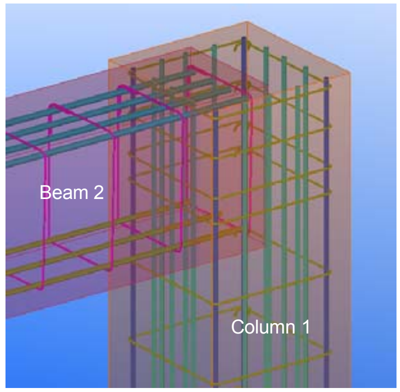
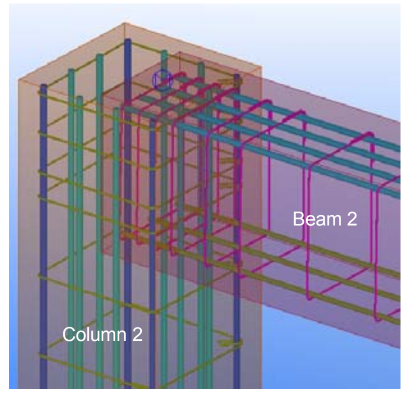
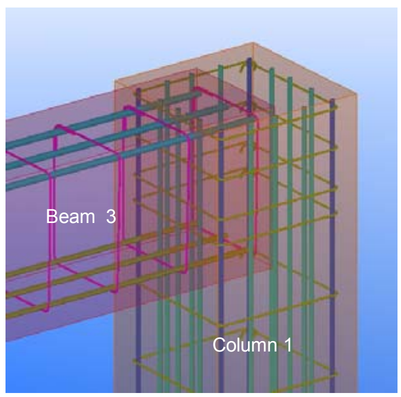
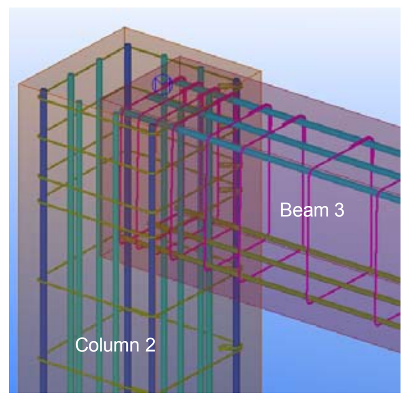
Bar Size	No. of Bars	Area (in^2)
#5	31	9.61
#6	22	9.68
#7	16	9.60
#8	13	10.27
#9	10	10.00

After applying these ‘must’ criteria and ‘want’ criteria, the author selects six alternative beam-column joints from the set of 72 possible combinations (from 24 beam alternatives and three column alternatives) to evaluate with the Tabular Method of CBA.

Beams 2, 3, and 6 (Figure 24) and Columns 1 and 2 (Figure 25) remain in consideration. Figure 26 shows combinations of these elements, which make up the six alternatives considered in this CBA example.

5.3 SELECTING BEAM-COLUMN ALTERNATIVES

With alternatives enumerated, the team can use the CBA system used to select one amongst them. Table 20 shows the four basic contexts of CBA: (1) Choosing from mutually-exclusive alternatives with equal dollars, (2) Setting priorities among non-exclusive proposals with equal dollars, (3) Setting priorities among non-exclusive proposals with unequal dollars, and (4) Choosing from mutually-exclusive alternatives with unequal dollars. Different decision contexts call for different decision methods. Selecting a beam or column alternative is an example of a decision involving mutually-exclusive alternatives with equal dollars. Should the alternatives considered have different costs, the difference is assumed to be marginal, so costs will not be addressed in the selection process.

<table>
<tr><th></th><th>Column 1</th><th>Column 2</th></tr>
<tr><td>Beam 2</td><td>
</td><td>
</td></tr>
<tr><td>Beam 3</td><td>
</td><td>
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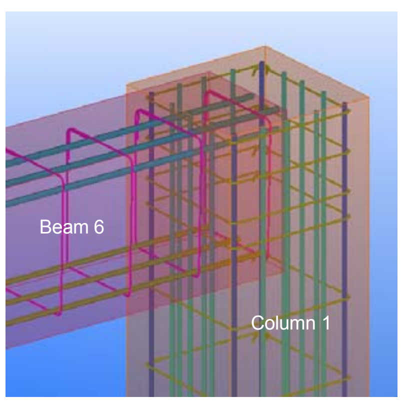
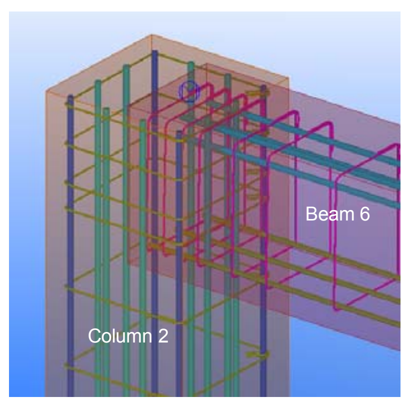
<tr><td>Beam 6</td><td>
</td><td>
</td></tr>
</table>

Figure 26. Alternatives considered in CBA

Table 20. Four basic contexts of CBA (from CBA Training course materials)

	Choosing from Mutually-Exclusive Alternatives	Setting Priorities among Non-Exclusive Proposals
With EQUAL dollars	CONTEXT NO. 1 MUTUALLY-EXCLUSIVE Alternatives with EQUAL dollars	CONTEXT NO. 2 NON-EXCLUSIVE Proposals with EQUAL dollars
With UNEQUAL dollars	CONTEXT NO. 4 MUTUALLY-EXCLUSIVE Alternatives with UNEQUAL dollars	CONTEXT NO. 3 NON-EXCLUSIVE Proposals with UNEQUAL dollars

5.4 DETERMINING FACTORS AND CRITERIA

Once decision-makers have developed alternatives, they can present them in a CBA table to compare them (this example illustrates the Tabular Method of CBA). The left-hand column of Table 21 lists factors. As in this example, some decision-makers display criteria in this table. Others display criteria separately. A decision-maker chooses which factors to consider depending on their ability to discern advantages of alternatives within that factor. If all alternatives have the same attribute in a given factor, that factor need not be considered because it does not help to discriminate between alternatives. This example presents only factors with advantages the author thought relevant. Another group of stakeholders or another set of alternatives may warrant different factors, as some factors may be company-specific (e.g., a fabricator may consider how fabrication of an alternative changes their current shop schedule).

Table 21. CBA table comparing beam-column joints (Part 1 of 3)

FACTORS	ALTERNATIVES											
	Column 1, Beam 2		Column 1, Beam 3		Column 1, Beam 6		Column 2, Beam 2		Column 2, Beam 3		Column 2, Beam 6	
SE-1. Total cross-sectional area of rebar in column Must Criterion: Total rebar area in column >= 9.5 in^2 Want Criterion: The least amount of rebar to fulfill must criterion is best												
Attributes:	9.60 in^2		9.60 in^2		9.60 in^2		9.48 in^2		9.48 in^2		9.48 in^2	
Advantages:							.12 in^2 fewer	10	.12 in^2 fewer	10	.12 in^2 fewer	10
SE-2. Total cross-sectional area of rebar in top of beam Must Criterion: Total rebar area in top of beam >= 3 in^2 Want Criterion: The least amount of rebar to fulfill must criterion is best												
Attributes:	3.16 in^2		3.00 in^2		3.16 in^2		3.16 in^2		3.00 in^2		3.16 in^2	
Advantages:			.16 in^2 fewer	20					.16 in^2 fewer	20		
SE-3. Total cross-sectional area of rebar in bottom of beam Must Criterion: Total rebar area in bottom of beam >= 1.8 in^2 Want Criterion: The least amount of rebar to fulfill must criterion is best												
Attributes:	1.80 in^2		1.80 in^2		1.80 in^2		1.80 in^2		1.80 in^2		1.80 in^2	
Advantages:	No advantage of any alternative											
SE-4. Spacing for concrete to bond to bars Must Criterion: Concrete must be able to enter the beam-column joint Want Criterion: The more bar surface area that can bond to concrete, the better (more clear space between bars preferred)												
Attributes:	Intersection		Intersection		2.5 in between beam and column rebar		Beam and column rebar touch		2.4 in between beam and column rebar		Intersection	
Advantages:					2.5 additional inches of clear space	90	Beam and column do not intersect rather than intersect	55	2.4 additional inches of clear space	85		
SE-5. Total weight of rebar per 1-foot section of joint Want Criterion: The lighter the better												
Attributes:	49.50 lb/ft		49.00 lb/ft		49.50 lb/ft		48.90 lb/ft		48.40 lb/ft		48.90 lb/ft	
Advantages:			.50 lb/ft less	15			.60 lb/ft less	20	1.10 lb/ft less	45		

Table 21. CBA table comparing beam-column joints (Part 2 of 3)

FACTORS	ALTERNATIVES											
	Column 1, Beam 2		Column 1, Beam 3		Column 1, Beam 6		Column 2, Beam 2		Column 2, Beam 3		Column 2, Beam 6	
SE-6. Maximum spacing between bars in column Must Criterion: Concrete must be able to enter the beam-column joint (spacing must be at least as large as aggregate) Want Criterion: The more homogeneous, the better (lower maximum spacing is best)												
Attributes:	4.2 inches		4.2 inches		4.2 inches		5.7 inches		5.7 inches		5.7 inches	
Advantages:	1.7 inches less space	65	1.7 inches less space	65	1.7 inches less space	65						
F-1. Intersection of beam and column reinforcement Must Criterion: The bars of the column and the bars of the beam cannot intersect Want Criterion: The beam bars and column bars will touch, but not intersect												
Attributes:	Intersection		Intersection		2.4 in between beam and column reinf.		Beam and column reinforcement touching, no intersection		2.4 in between beam and column reinf.		2.4 in between beam and column reinf.	
Advantages:					Bars do not touch or intersect	50	Bars touch rather than not touch	100	Bars do not touch or intersect	50	Bars do not touch or intersect	50
F-2. Number of bends necessary for beam and column bars not to intersect Want criterion: Fewer bends are better												
Attributes:	1 bend		2 bends		0 bends		0 bends		0 bends		0 bends	
Advantages:	1 bend fewer	10			2 bends fewer	25	2 bends fewer	25	2 bends fewer	25	2 bends fewer	25
F-3. Bar availability Must Criterion: Bars must be available for use Want Criterion: The shorter the lead time for a bar, the better												
Attributes:	#7 and #8 bar are readily available		#7 bar is readily available, #9 bar available in 2 weeks		#7 and #8 bar are readily available, #9 bar available in two weeks		#7 and #8 bar are readily available		#7 and #8 bar are readily available, #9 bar available in two weeks		#7 and #8 bar are readily available, #9 bar available in two weeks	
Advantages:	Material is most readily available	40					Material is most readily available	40				

Table 21. CBA table comparing beam-column joints (Part 3 of 3)

FACTORS	ALTERNATIVES											
	Column 1, Beam 2		**Column 1, Beam 3**		**Column 1, Beam 6**		**Column 2, Beam 2**		**Column 2, Beam 3**		**Column 2, Beam 6**	
F-4. Number of bars used												
Want Criterion: The less bars, the better												
Attributes:	23 bars		22 bars		18 bars		19 bars		18 bars		18 bars	
Advantages:			1 bar fewer	4	5 bars fewer	10	4 bars fewer	8	5 bars fewer	10	5 bars fewer	10
F-5. Number of hooks in joint												
Want Criterion: Fewer hooks are better												
Attributes:	0 hooks		0 hooks		0 hooks		0 hooks		0 hooks		0 hooks	
Advantages:	No advantage of any alternative											
F-6. Number of layers of rebar in top of beam												
Must Criterion: At least one layer of tension reinforcement is required												
Want Criterion: Fewer layers of reinforcement are preferred												
Attributes:	1 layer		1 layer		2 layers		1 layer		1 layer		2 layers	
Advantages:	1 less layer	5	1 less layer	5			1 less layer	5				
F-7. Number of different bar sizes used												
Want Criterion: Fewer different bar sizes is preferred												
Attributes:	2 sizes		2 sizes		3 sizes		2 sizes		3 sizes		3 sizes	
Advantages:	1 less size	5	1 less size	5			1 less size	5				
GC-1. Reusable formwork												
Want Criterion: Reusable formwork is preferable												
Attributes:	Reusable forms		Reusable forms		Reusable forms		Reusable forms		Reusable forms		Reusable forms	
Advantages:	No advantage of any alternative											
TOTAL IMPORTANCE:		125		114		240		268		245		95

5.4.1 STRUCTURAL ENGINEER'S FACTORS

Table 21 lists six factors (labeled SE-1 through SE-6) the author, with her structural engineer's hat on, considered when assessing a set of beam-column joint alternatives. Decision-making is subjective, so factors selected will always reflect the background and preferences of the decision-maker(s). Factors considered will vary according to suitability to the project, the specific alternatives, and the decision-maker(s). In this example, the 'structural engineer's factors' considered reflect the author's perception of relevance based on her background.

The factor **SE-1. Total cross-sectional area of rebar in column** examines whether or not the area of rebar in the column satisfies the 'must' criterion set out in ACI 318-05, which mandates column strength based on applied loads. An engineer calculates the required rebar area based on required tension strength for the column. Strength calculations include a strength reduction factor, φ (ranging from .65 to .90), to ensure design is conservative (i.e., column strength exceeds the applied loading). Further, tension strength requirements assume rebar yields at its nominal strength (i.e., grade 60 steel yields at 60 ksi) though in testing, the nominal yield stress is at least 3 standard deviations from the actual yield stress (i.e., at least 99% of bars tested have yield at a stress higher than 60 ksi)(Nowak et al. 2005). Nowak et al. (2005) suggest rebar actually yields at $1.13f_y$. ACI 318 requires 9.50 in^2 of rebar for columns in this example based on the calculation that includes a strength reduction factor, $\varphi = .65$ (ACI 318, section 9.3.2.2) and assumes rebar yields at 60 ksi. Thus, an engineer may try rebar configurations with up to 10% less rebar than specified (Moehle 2004) . Following this logic, a column with 9.48 in^2 of rebar is a viable alternative; although strictly-speaking ACI 318 requires 9.50

in^2 of rebar for a column this size (‘must’ criterion). If required by the permitting agency, the engineer can perform calculations using mill certifications that list the actual yield stress of a bar.

The ‘want’ criterion expresses preference for minimizing the total rebar area to reduce material costs and minimize the reinforcement ratio. Minimizing the reinforcement ratio is thought to minimize congestion. However, in some cases, a smaller total area of rebar may not reduce congestion, as that configuration may include more small bars than one with a greater total area, which may actually contribute to congestion.

The factor **SE-2. Total cross-sectional area of rebar in top of beam** examines whether or not the area of rebar in the top of the beam satisfies the ‘must’ criterion set out in ACI 318, which mandates rebar area necessary for a beam to meet strength and ductility requirements. If grade 60 rebar is used, a ‘must’ criteria for ACI is that at least 3.00 in^2 of rebar be present in the top of the beam.

The ‘want’ criterion is to minimize the total area for reasons stated previously.

The factor **SE-3. Total cross-sectional area of rebar in bottom of beam** examines whether or not the area of rebar in the bottom of the beam satisfies the ‘must’ criterion set out in ACI 318. A beam of this size requires a rebar area of at least 1.80 in^2.

The ‘want’ criterion for this factor is also to minimize the total area.

The factor **SE-4. Spacing for concrete to bond to bars** examines whether or not space between bars is sufficient for concrete to flow through. To minimize slip between the concrete and the rebar, concrete needs to bond to as much rebar surface as possible. For concrete to reach the rebar surface, sufficient space must exist between rebar for concrete to flow through. Thus, more space for concrete to flow through helps promote bonding.

The 'must' criterion states concrete must bond to rebar at some place in the joint. If the joint was made entirely of rebar, structural failure may occur. For example, rebar alone may buckle under compressive loading, which could cause failure. However, concrete is strong in compression, so a joint with both rebar and concrete is less likely to fail under the same loading that could buckle rebar alone.

The 'want' criterion states more spacing is better, which reflects the author's preference for maximum bonding area. Larger spacing between bars promotes easier flow of concrete between bars, which in turn allows bonding between the concrete and rebar.

The factor **SE-5. Lineal weight of rebar in joint** examines the weight of rebar per foot of length in the joint. This factor contains only a 'want' criterion, which is to minimize weight, reflecting the structural engineer's preference to reduce material cost (rebar cost is often calculated per ton, so according to this calculation, minimizing weight minimizes material cost) and amount of material to be placed. In some cases, a rebar fabricator may favor more weight if it makes placing easier (e.g., fewer heavier bars to be placed).

The factor **SE-6. Maximum spacing between column bars** assesses homogeneity of the column through spacing of bars. An element with more bars spaced closer together are more homogeneous than an element with one large bar, so the higher the maximum spacing, the less homogeneous the material. A structural engineer may focus more on homogeneity of material than on the number of bars used.

The 'must' criterion for this factor requires sufficient spacing for concrete to flow between bars. This is a function of aggregate size in the concrete mix (a design choice not determined within the scope of this example), but is on the order of 1 inch for this example (Mehta and Monteiro 2006). Homogeneity of material is a preference, not a requirement. Homogeneity promotes better ductility and column behavior, as forces distribute more evenly between bars. The 'want' criterion (the more homogeneous, the better) captures this preference.

5.4.2 REBAR FABRICATOR'S FACTORS

Table 21 also lists seven factors (labeled F-1 through F-7) the author, with her rebar fabricator's hat on, may consider when assessing the same set of beam-column joint alternatives.

The factor **F-1. Intersection of beam and column reinforcement** addresses whether or not beam and column reinforcement intersect if placed as specified. If plans show intersecting beam and column reinforcement, rebar must be bent or otherwise adjusted in the field to place it. For instance, if both beam and column reinforcement lie on the centerline of the joint, rebar placers will have to move either the beam or column bar will to place the joint.

Although bars cannot physically intersect, intersection may be shown on plans. Even some 3D modeling tools may allow bars to intersect, ignoring physical reality. A 'must' criterion for this factor could state, "The bars coming into the joint cannot intersect." However, in most cases, if bars intersect on plans, one bar is moved, bent, or otherwise forced into place in the field, so this is not a 'must' criterion.

The ‘want’ criterion states the fabricator’s preference for bars in the joint to be touching, thereby eliminating the need to use spacers to place the joint.

The factor **F-2. Number of bends necessary for beam and column bars not to intersect** lists the number of bends necessary to place rebar for the alternative as specified. The author lists attributes assuming a bar must be bent once to eliminate an intersection shown on plans (e.g., bar in the beam is bent to thread through column reinforcement). In reality, bars may not be bent into place in the field, instead they may just be moved over.

If many bends are necessary over a small length of bar, a ‘must’ criterion from CRSI would be considered; however, in this example, ample length is provided for bends, so Table 21 does not contain a ‘must’ criterion for this factor.

The ‘want’ criterion states that fewer bends are better; as they save fabrication time.

The factor **F-3. Bar availability** addresses whether or not bars of a given size are available for use on the project. This factor accounts for the inventory of the fabricator and the lead time to get bars from the steel mill.

The ‘must’ criterion states that bars must be available for use when required by the rebar placing schedule. This criterion does not stipulate bars be available early, just that they be available by the time they must be placed.

The ‘want’ criterion states the fabricator’s preference to use bars available sooner rather than later, as this allows placement to start earlier. Most fabricators keep a large inventory of bars, so they can provide bars for a job without long lead times. However, fabricators do not often keep a large inventory of #14 or #18 bars, so if a job requires large quantities (on the order of 120T) of either of these, the fabricator must coordinate with the mill to guarantee on-time rebar delivery (Richenberger 2008).

The factor **F-4. Number of bars** counts the total number of bars to be placed. The 'want' criterion in this factor is somewhat contradictory to the 'want' criterion in the structural engineer's homogeneity factor.

The 'must' criterion states that the total area of the bars meets the area requirement in ACI 318. The 'want' criterion states that the fewer bars are better because it is faster to place fewer bars; provided bars are not larger than #11 (placing #14 and #18 bars requires a crane, so productivity rates decline from #11 [5.31 lb/foot] to #14 [7.65 lb/foot] to #18 [13.60 lb/foot]). Note rebar of any size or length may be placed with a crane. However, two ironworkers can manually lift a standard 40-foot length of #4 - #11 bar, but most cannot lift a 40-foot #14 or #18 bar (Bennion 2007).

Using CBA, one can consider this criterion in this factor, despite its opposition to the structural engineer's homogeneity 'want' criterion. CBA addresses this difference in viewpoint when importances are decided for the advantages. The advantage of alternative 1 over alternative 2 with respect to this criterion may be offset by the advantage of alternative 2 over alternative 1 with respect to the homogeneity 'want' criterion. Indeed, opposing criteria may spark a discussion about the performance characteristics to be expected from a more homogeneous joint compared to the schedule implications of having to place more bars. This discussion will be anchored to the specific advantages of each alternative in terms of homogeneity and number of bars, so the stakeholders can make an informed decision about which is more important.

The factor **F-5. Number of hooks in joint** lists the number of hooks in a joint. Ends of bars cannot carry as much load as the center, indeed, the very tip of a bar carries no load, so bars must have ample length to develop (ACI 318, Chapter 12 defines 'ample length'). In lieu of development length, bars may hook into joints or be fitted with a mechanical anchor (e.g., a T-head). Unanchored bars may pull out of a joint when loaded, which renders the bar useless. End anchors, hooks, or ample development length prevents bars from pulling out of joints. This set of alternatives exclusively uses straight bars designed to have ample development length.

Hooks take up space in a joint and may lie out of the plane of reinforcement. In tight placement situations (e.g., stirrups in a seismically-detailed column), hooks may intersect with other bars or make it difficult to thread a bar into place. Thus, minimizing the number of hooks is the 'want' criterion.

The factor **F-6. Number of layers of reinforcement in top of beam** compares the number of layers of reinforcement in the top of the beam for each alternative.

The 'must' criterion states the minimum requirement for layers of reinforcement, that is, one layer is necessary in the top of the beam to provide strength for the beam. In some cases, loading or concrete properties eliminate the need for rebar. However, alternatives considered in this example require rebar.

The 'want' criterion expresses the fabricator's preference for fewer layers of reinforcement to minimize the need for spacers to maintain a minimum distance between layers of rebar so as to allow concrete to go in-between.

The factor **F-7. Number of different bar sizes used** compares the number of bar sizes used in each of the beam-column joint alternatives.

This factor does not have a 'must' criterion; no code rules govern how many different bar sizes can be specified for a beam-column joint.

The 'want' criterion expresses preference for fewer different bar sizes to avoid matching problems onsite (e.g., Tommelein 1998). Use of different bar sizes can reduce productivity of placing rebar and increase the likelihood of mistakes occurring. It can also increase the time for detailing and review of shop drawings, as more quantities need to be checked, bar lists are longer, etc.

5.4.3 General Contractor's Factor

In addition to factors of concern to the structural engineer and rebar fabricator, the general contractor may bring others to the table. Table 21 shows factor GC-1 that the author considered with her general contractor's hat on, which compares whether or not formwork used for each alternative is reusable. The author considers a factor relevant if a discernable difference exists between one alternative and another. Thus, for the alternatives considered, general contractors may not bring many factors to the table, as element dimensions do not differ and only marginal differences exist in terms of concrete area.

The factor **GC-1. Reusable formwork** examines whether or not forms can be used repeatedly for each of the alternatives. Reusable formwork requires alternatives have the same concrete volume and dimensions. This saves time constructing forms, and saves material as well.

This factor does not have a 'must' criterion. The 'want' criterion expresses the preference for reusable formwork.

5.5 SUMMARIZE ATTRIBUTES OF EACH ALTERNATIVE

Table 21 lists attributes of each alternative, each corresponding to a factor. In some cases, the process of listing attributes may lead to refinement or consideration of new factors. For instance, when this example table was developed, factors included 'Rebar area in beam' and 'Rebar area in column.' However, it became clear that these factors were not specific enough, so 'Rebar area in beam' was split into 'Total cross-sectional area of rebar in top of beam' and 'Total cross-sectional area of rebar in bottom of beam.'

Attributes reflect data wherever possible. For example, within the 'Total cross-sectional area of rebar in top of beam' factor, the attributes of each alternative show the calculated values of total rebar area. Listing data as attributes makes the CBA process more transparent and defensible, as the basis for a decision is clear.

5.6 DETERMINE THE ADVANTAGES OF EACH ALTERNATIVE

Table 21 lists the dissimilarities or differences that make up the advantages of each alternative (Suhr 1999). Advantages reflect the backgrounds and expertise of the stakeholders who determine them. For instance, Table 21 reflects the author's understanding of structural engineers', fabricators', and general contractors' values. If the group of stakeholders participating in a CBA analysis is larger than 20, separate 'focus groups' of about 20 stakeholders will each complete a CBA analysis and then merge them to make a decision.

5.7 ASSIGN A DEGREE OF IMPORTANCE TO EACH ADVANTAGE

To assign the relative importance of each advantage, highlight the most-important advantage in each factor to focus attention when identifying the paramount advantage in Table 21. From amongst the most-important advantages, select the most important most-important advantage. This is the paramount advantage, used to establish a scale of importance. The paramount advantage in this case is 'Bars touch rather than not touch' in the factor 'F-1. Intersection of beam and column reinforcement.' The author assigned this advantage an importance of 100 (circled in red on Table 21). All other importances will be established relative to this.

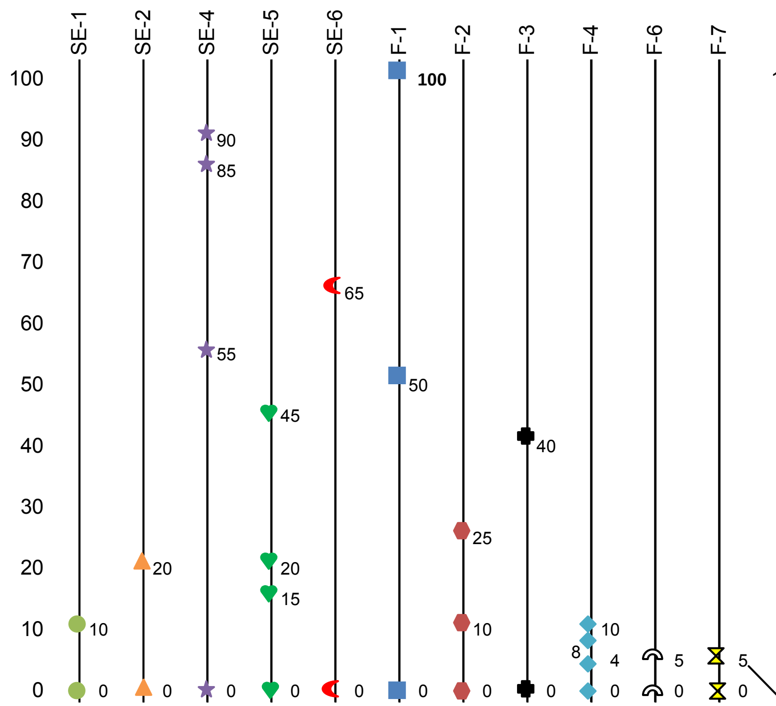
As with some of the other steps in CBA, assigning a degree of importance is a subjective process. Stakeholders assign importance based on their background and expertise, as well as based on the purpose and circumstances of the decision (Suhr 1999). Suhr (1999) also recommends considering the needs and preferences of the customers and other stakeholders when assigning importance. Finally, he explains, "in the typical situation,… an advantage of almost zero has an importance of almost zero" (Suhr 1999, p. 102).

One method to establish importance is the 'Defender-Challenger' method, which makes pair-wise comparisons between advantages to determine their rank. To begin, list all advantages on Post-it™ notes and place them on a table or wall. Assign an importance of 0 to one end of the table and at the other end, stick the paramount advantage with an importance of 100. Select a 'defender' and a 'challenger' and compare them. For example, select the advantage '.12 in^2 fewer' relative to the least-preferred attribute, 9.60 in^2 in the 'SE-1. Total cross-sectional area of rebar in column' factor as the Defender. Select the advantage '.16 in^2 fewer' relative to the least-preferred attribute, 3.16 in^2 in the 'SE-2. Total cross-sectional area of rebar in top of beam' factor as the Challenger. Ask, "Is .16 in^2 fewer than 3.16 in^2 total cross-sectional area of rebar in the top of the beam more important or less important than .12 in^2 fewer than 9.60 in^2 total cross-sectional area of rebar in the column?” The ‘winner’ of this challenge is compared to the successive advantages until it ‘loses.’ This provides an ordering of the advantages. Place the ordered advantages on the table or wall between 0 importance and the paramount advantage according to scale. Figure 27 shows results of the author’s defender-challenger analysis for this example.

CBA requires stakeholders postpone making value judgments until they assign importance to advantages. For this example, assigning importance is the last subjective step of the decision-making phase; so arguably, it is the last responsible moment to make value judgments. The last responsible moment refers to the point in time when failing to make a decision eliminates an alternative. In the context of CBA, it refers to the point in time when failing to make a value judgment eliminates the ability to make a decision. Previous steps in CBA help inform stakeholders, but assigning importance requires subjective judgments to select an alternative.

When assigning importance, stakeholders may have competing values and may struggle to reach agreement about the importance of a given advantage. Different groups of stakeholders may decide on different importances for advantages. However, through discussion, importances can usually be agreed upon (Suhr, personal communication, 12/11/08). For complex decisions, CBA requires importances be recorded on a table, so future decision-makers can understand how decisions were made.

Importance of Advantages



Value	Factor(s)	Advantage(s)
100	F-1	Bars touch rather than not touch or intersect
95		
90	SE-4	2.5 in more clear space than intersection
85	SE-4	2.4 in more clear space than intersection
65	SE-6	1.7 in less space than 5.7 in
55	SE-4	Beam and column bars do not intersect rather than intersect
50	F-1	Bars do not touch or intersect rather than intersect
45	SE-5	1.10 lb/ft less lineal weight than 49.50 lb/ft
40	F-3	Material is most readily available vs. available in 2 weeks
25	F-2	2 bends less than 2 bends
20	SE-2; SE-5	.16 in^2 less than 3.16 in^2; .60 lb/ft less lin. wt. than 49.50 lb/ft
15	SE-5	.50 lb/ft less lineal weight than 49.50 lb/ft
10	SE-1; F-2; F-4	.12 in^2 less area than 9.60 in^2; 1 less bend (1 vs. 2); 5 less bars (18 vs. 23)
8	F-4	4 less bars (19 vs. 23)
5	F-6; F-7	1 less layer than 2 layers; 1 less size than 3 sizes
4	F-4	1 bar less than 23 bars

Figure 27. Importance scale for CBA analysis

5.8 CALCULATE TOTAL IMPORTANCE

Total the importance of advantages of each alternative to identify the preferred alternative. The bottom row of Table 21 lists total importance for each alternative. Column 2 and Beam 2 (Total importance = 268) is the preferred alternative based on the author's rationale.

5.9 APPLICABILITY OF THIS EXAMPLE TO FUTURE CBA ANALYSES

The CBA analysis presented in this chapter reflects the background and expertise of the author. However, some pieces of it could be re-used for another beam-column joint decision involving a different group of stakeholders. Indeed, Table 21 lists factors the author considered relevant for this decision. Certain factors would likely be applicable to other stakeholders as well, for instance, factors concerning rebar area (SE-1, SE-2, and SE-3) that reflect ACI 'must' criteria,. Factor F-2, Number of bends necessary for beam and column bars not to intersect, contains only 'want' criteria for this example. However, it could include the CRSI 'must' criteria, "A three-foot length of rebar cannot be bent at more than six points in one plane, nor can it be bent in more than one plane" (CRSI 2009), which would make it more general.

As stakeholders use CBA for more and more decisions, they can develop a more general set of factors to re-use for each CBA analysis involving a specific type of decision (e.g., beam-column joints). Further, they can develop stakeholder- and company- specific factors and criteria to use for CBA. Table 22 shows a general CBA table for a decision about a beam-column joint. It lists some of the factors considered in this example (Table 21), and also leaves room for stakeholder-specific factors. The factors listed in Table 22 would be applicable to *any set* of beam-column joint alternatives, as they contain ACI and CRSI ‘must’ criteria. Table 22 omits some factors considered in this example (Table 21), as they reflected the author’s viewpoint, not necessarily factors applicable to all beam-column joint decisions.

Re-using factors saves time in developing a CBA table. Similarly, BIM tools can save time in determining attributes and advantages listed in CBA tables. Provided stakeholders model (or have access to a model with) design alternatives, they can extract attributes from it. They may also automate the determination of advantages by programming must and ‘want’ criteria into the BIM model so advantages can be extracted from it directly. Thus, if stakeholders decide to develop another alternative, evaluating it with CBA is a straight-forward process that requires minimal additional time.

Finally, if the stakeholders perform the defender-challenger exercise and develop a scale of importance, they may find assigning importance easier. If stakeholders consider alternatives and develop preference curves (i.e., charts that compare attributes in a given factor to importance of advantages), they can assign importance to an advantage based on the attribute alone! The author did not develop preference curves for this example because she did not have enough data to confidently do so. However, another group of stakeholders be able to.

Table 22. General CBA table for beam-column joint

FACTORS	ALTERNATIVES					
	Alternative 1		Alternative 2		Alternative 3	
SE-1. Total cross-sectional area of rebar in column Must Criterion: Total rebar area in column must satisfy ACI 318, Section 10.5 Want Criterion: The least amount of rebar to fulfill must criterion is best						
Attributes:						
Advantages:						
SE-2. Total cross-sectional area of rebar in top of beam Must Criterion: Total rebar area in top of beam must satisfy ACI 318, Section 10.5 Want Criterion: The least amount of rebar to fulfill must criterion is best						
Attributes:						
Advantages:						
SE-3. Total cross-sectional area of rebar in bottom of beam Must Criterion: Total rebar area in bottom of beam must satisfy ACI 318, Section 10.5 Want Criterion: The least amount of rebar to fulfill must criterion is best						
Attributes:						
Advantages:						
SE-6. Maximum spacing between bars in column Must Criterion: ACI 352 requires at least 1.5 inches of clear space between column bars Want Criterion: The more homogeneous, the better (lower maximum spacing is best)						
Attributes:						
Advantages:						
F-1. Intersection of beam and column reinforcement Must Criterion: The bars of the column and the bars of the beam cannot intersect Want Criterion: The beam bars and column bars will touch, but not intersect						
Attributes:						
Advantages:						
F-3. Bar availability Must Criterion: Bars must be available for use when required by the rebar placing schedule Want Criterion: The shorter the lead time for a bar, the better						
Attributes:						
Advantages:						
F-4. Number of bars used Want Criterion: The less bars, the better						
Attributes:						
Advantages:						
F-6. Number of layers of tension reinforcement Must Criterion: At least one layer of tension reinforcement is required Want Criterion: Fewer layers of reinforcement are preferred						
Attributes:						
Advantages:						
Stakeholder-specific factors Must Criterion: Want Criterion:						
Attributes:						
Advantages:						
TOTAL IMPORTANCE:						
TOTAL COST:						

5.10 CONCLUSIONS

CBA is a decision-making system that complements lean practices such as set-based design and collaboration. This chapter presented an example of the second and third phases of the CBA process for moderately complex decisions – the innovation and decision-making phases. In this case, for selecting rebar for a beam-column joint. The innovation phase consists of developing a set of alternatives (e.g., with set-based design) and determining the factors necessary to highlight the differences between these alternatives. The decision-making phase consists of determining factors and criteria, summarizing the attributes of each alternative, determining advantages of each alternative, assigning a degree of importance to each alternative, and totaling the importance of advantages to actually choose an alternative.

This chapter does not discuss the fourth and fifth phases of CBA, reconsideration and implementation. The reconsideration phase allows decision-makers to develop more alternatives or consider more factors (and criteria within them) if necessary (i.e., if the stakeholders are uncomfortable with the decision). If stakeholders consider more alternatives, they can use the same scale of importance. If they select a new paramount advantage, the scale simply grows (i.e., the paramount advantage may have an importance of 135) to accommodate it. This way, the stakeholders do not need to re-assign importance to the advantages already determined. The implementation phase applies the decision and makes adjustments if necessary during implementation.

In this example, the decision-making phase applies the tabular method, which displays alternatives, factors, criteria, attributes, advantages, importances, and total importances in a table format. Deciding the importance of each advantage spurs discussion among stakeholders about their values. This discussion can foster a shared understanding of the project goals and how each stakeholder contributes to realizing them. Once agreed upon, the table records the importance of each advantage.

Documenting all of this information helps stakeholders develop general CBA tables for similar decisions. The first time stakeholders use CBA for decision-making, it may be a time consuming process. Much of the time is spent during the stage-setting phase and the innovation phase – defining the decision's purpose and developing a set of alternatives. However, as decisions begin to repeat from project to project, general CBA tables can be developed, saving time in the innovation and decision-making phases in future CBA analyses.

CHAPTER 6. CASE STUDY: EXPANSION OF THE USC SCHOOL OF CINEMATIC ARTS COMPLEX

6.1 INTRODUCTION

This chapter describes the design phase of the Expansion of the University of Southern California (USC) School of Cinematic Arts. This project stemmed from a donation by the Lucasfilm Foundation (set up by film director George Lucas) to USC. The project is located on the University of Southern California campus in Los Angeles, California. Figure 28 shows a satellite view of the USC campus. The ‘A’ marker points to the project site. The surrounding buildings limited laydown area for the project. Figure 29 shows a rendering of this 137,000 ft^2 project, which includes 23 conference rooms, eight classrooms, eight screening rooms, a café, and exhibit space (USC School of Cinematic Arts 2009). USC hired an integrated project delivery team to design and construct the School of Cinematic Arts. They required the project be fully detailed in a BIM model that would support design and construction coordination, as well as operations and maintenance once the project was complete (Luth 2008).

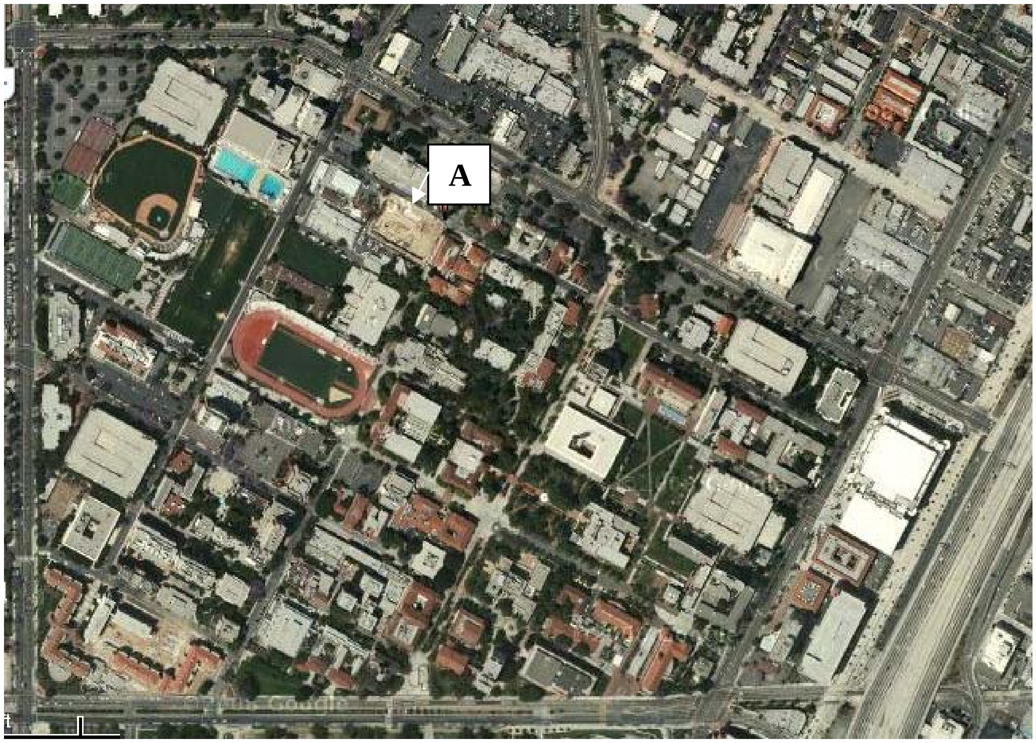


Figure 28. Satellite view of the USC campus, construction site labeled (image from maps.google.com, search “USC campus”, visited 4/13/09)

Figure 29. Rendering of the USC School of Cinematic Arts (image from http://cinema.usc.edu/about/giving/building-campaign.htm, visited 4/13/09)

Building Information Modeling (BIM), early collaboration, performance-based design, and set-based design led to the development of an innovative structural system designed for prefabrication and speedy erection. The design team, required by the donor to "do something different" and meet seismic requirements that limit unreduced floor accelerations to 1.0 g, explored many lateral system alternatives (Luth et al. 2008).

6.2 COMPANY BACKGROUNDS

Gregory P. Luth & Associates, Inc. (GPLA) held the structural engineering design contract for the USC School of Cinematic Arts Complex Expansion project. CMC Fontana held the rebar contract for this project.

6.2.1 GPLA BACKGROUND

GPLA, based in Santa Clara, California (GPLA 2009), works on challenging structural engineering projects, primarily in the private sector. Greg Luth, PhD, SE, is President and Chief Engineer of GPLA. He focuses on constructability during design, and encourages this practice across the company. He attended the Rebar Workshop in August, 2006 and suggested the USC project as a case study based on the innovative rebar design, fabrication, and placement processes.

6.2.2 CMC FONTANA BACKGROUND

CMC Fontana, based in Etiwanda, California, worked with GPLA to develop the rebar fabrication and placing plan. GPLA and CMC Fontana met "quite a few times" throughout the design phase of the project to discuss fabrication and erection capabilities and opportunities on the project (Stowers 2008). CMC Fontana used views of the BIM model GPLA created, but ultimately detailed the project with RebarCAD because detailers were familiar with it and it integrates with estimating and accounting software "seamlessly" (Stowers 2008).

6.3 PROJECT BACKGROUND

The design team used performance-based design to develop an innovative shear rocking wall system that boasts superior structural performance (compared to a structure designed using traditional methods) in laboratory tests. The system comprises 100 cages of prefabricated rebar that are flown directly from the truck into place. The team's focus in the design phase on detailed modeling, constructability, and prefabrication paid off; the construction team was able to place ten cages per day whereas the schedule had anticipated two cages per day (Luth et al. 2008). This chapter describes the team's efforts to design for constructability and the conversations they had to ensure the structure could be prefabricated. This case study illustrates the need not only to have subcontractors join the team early to share their unique expertise with the design team, but also for the team to have language and tools (such as set-based design and BIM) at their disposal to collaborate effectively. Further, it highlights the need for structural engineers to *detail* structures to visualize congestion and develop solutions to help minimize it.

6.4 PROGRAMMING PHASE OF THE PROJECT

The programming phase of the design process (Figure 3) comprises understanding the function, purpose, use, goals, and context for the structure. Programming includes developing a milestone schedule and a preliminary budget (typically used to secure financing). It also helps owners, architects, engineers, and contractors articulate 'must' and 'want' criteria for the project.

6.4.1 ‘MUST’ CRITERIA FOR THE PROJECT

The design process began for GPLA with a set of ‘must’ criteria. USC’s seismic performance specification stated the building was to remain operational in the event of an earthquake with a 1,000-year return period. They also required the building be designed for a 100-year lifetime (a 50-year lifetime is a more common ‘must’ criterion). Both the building donor and the building owner had “bought into” the stucco façade by the time the structural engineer was brought on to the project team, so the structural system selected needed to support it. Limited laydown area was available onsite, necessitating the design support prefabrication and just-in-time delivery. In addition to ‘must’ criteria for the design product, the donor and owner’s project manager required use of a 3D BIM model for project design and coordination. This required a strict naming convention so the design team could maintain an updated project model despite using different BIM software. The architect used AutoDesk Revit, GPLA used Tekla Structures, CMC Fontana used RebarCAD, and other subcontractors used their own field-specific 3D modeling software (Luth 2008).

6.4.2 ‘WANT’ CRITERIA CONCERNING BIM MODEL

Each member of the integrated project delivery team had different expectations and ‘want’ criteria for the BIM model.

The owner’s project manager expected the BIM model to show “all HVAC, electrical, plumbing, fire protection, architectural, and structural elements so these could be coordinated in the model” (Luth 2008). Further, he expected the structural drawings (generated from the BIM) to show all penetrations through walls and steel beams to ensure the MEP work would fit through penetrations with no clashes. He thought that if these expectations were met, money could be saved during the construction phase of the project. The owner expected the MEP team to develop libraries with MEP objects that would be used to integrate the BIM model (Luth 2008).

The owner's Facility Manager expected the BIM model to "contain a 3D graphical model linked to a database containing the specifications and periodic maintenance schedules and records of all of his mechanical equipment and piping that his staff can use interactively during the daily operation of the physical plant" (Luth 2008).

The general contractor (GC) expected the BIM model to "contain accurate quantities of concrete, steel, windows, doors, walls (types and finishes), and MEP equipment for use by the estimators" (Luth 2008).

The architect wanted the BIM model to "facilitate the coordination of all the MEP, structural, and acoustical items as well as facilitate accurate and comprehensive scheduling of doors and windows" (Luth 2008).

The structural engineer expected the BIM model to "contain all of the fabrication details for the structural steel, comprehensive steel quantities including plates, bolts, and welds, and [the model] will be used to produce steel shop drawings. The BIM will contain all concrete and reinforcing quantities. The BIM will accurately show all the connections between steel members and between steel and concrete members. The BIM will accurately show the details of the reinforcing steel in a manner that will facilitate rebar placement" (Luth 2008).

After determining the 'must' and 'want' criteria, the design team moved on to the Schematic Design phase of the project.

6.5 SCHEMATIC DESIGN (SD) PHASE OF THE PROJECT

During Schematic Design (Figure 3), the project team (at this phase typically consisting of an owner, an architect, and a pre-construction contractor) determines building topology, material, preliminary construction sequence, required skills for future team members, and knowledge required to fully develop the project plans and schedule. They also determine “enabling details” for the project; details that could be the difference in the structure being built or not. Enabling details on this project included ensuring the structural system supported the stucco façade and ensuring a 100-year building (Luth et al. 2008).

Structural engineers may work with concept sketches from architects in this phase to develop structural schematics. Schematic Design can be one of the longest phases in the design process, as this is when they can develop and consider high-level alternatives. These alternatives contain enough detail to develop a sense of cost; “typical details” would show rebar, but project-specific rebar detailing would not be developed yet. GPLA believes design quality comes from good Schematic Design because this is when structural engineers explore the design space and think broadly about innovative solutions at a high level of abstraction. This phase concludes by the owner selecting a Schematic Design from among several selected by the design team. The design space thereby narrows and constrains the breadth of alternatives available to explore in greater detail.

During Schematic Design, GPLA developed a set of three structural system alternatives to meet the seismic performance criteria. Alternatives included (1) a steel moment resisting frame, (2) an “avant-garde” precast concrete wall-steel beam system, and (3) a cast-in-place (CIP) wall-steel column system. The steel moment resisting frame presented two challenges. First, the frame would be very flexible, so damage could result from a small earthquake. Second, installing stucco would require many joints, which would compromise the architectural appearance of the building. The precast concrete wall-steel beam system cost more than the other two systems and did not appear to offer enough schedule savings to justify the additional expense. GPLA appreciated the predictable limit states and replaceable fuses of this system. The CIP wall-steel column system facilitated easy stucco installation and matched the contractor's preference for a CIP system (Luth 2006). The team decided to pursue the CIP wall-steel column system. This decision released work for Design Development.

6.6 DESIGN DEVELOPMENT (DD) PHASE OF THE PROJECT

Structural engineers begin to detail the selected schematic in the Design Development phase (DD) (Figure 3). DD involves selecting the particular structural system, considering MEP systems, collaboration with the rebar subcontractor to develop rebar configurations and construction sequencing, and re-visiting "enabling details." On this project, DD included developing the CIP wall-steel column system to accommodate the stucco façade, detailing the structural system with BIM software Tekla Structures, and testing elements of the structural system.

6.6.1 INNOVATION IN DD: DEVELOPING THE SHEAR ROCKING WALL SYSTEM

Having selected the CIP wall-steel column structural system, GPLA needed to detail it to meet the owner's performance criteria. To do so, GPLA designed, detailed, and tested a shear rocking wall system consisting of ductile linked shear walls and rocking shear panels (Luth 2008). The shear walls comprise concrete, steel columns, steel fuses, and shear lugs. The concrete walls act as panels connected to the foundation with shear lugs.

CIP wall panels connect to the steel columns with steel fuses, so-called ‘butterfly plates.’ The CIP wall panels and the steel columns “rock” on the foundation during an earthquake. Shear lugs permit the walls to rock on the foundation. Butterfly plates “transfer vertical forces from the overturning moment of the CIP panel to the steel columns” (Luth et al. 2008). Butterfly plates engage during design level earthquakes, but during a smaller seismic event, the building behaves elastically (Luth et al. 2008). This means that structural damage during larger earthquakes is localized to the plates, which can as necessary be tested and repaired more easily than a conventional lateral system can be (e.g., a steel moment frame). Butterfly plates can be found, tested, and replaced as necessary after an earthquake with minimal damage to the surrounding walls and columns. This repair could restore the structure to its pre-earthquake performance level. The BIM model that the integrated project team develops shows USC the location of the plates, so after an earthquake, a construction team would know exactly where to remove stucco and concrete to replace the damaged plates. Figure 30 shows the butterfly plate in the Tekla Structures model that GPLA will give to USC upon project completion.

Once the butterfly plates were designed, they were tested at Stanford University to determine the appropriate earthquake response modification factor “R.” Figure 31 shows one such test. Note the deformation of the slits that dissipate energy during an earthquake. Testing supported an R-value of 5.5, which was used by the City of Los Angeles in their review of the project (Luth et al. 2008). Professor Krawinkler at Stanford University and Jim Ship and Brian McDonald at Exponent also reviewed the structural design for engineering validity and constructability (Luth 2006). Luth et al. (2008) elaborate on structural testing and permitting requirements during DD.

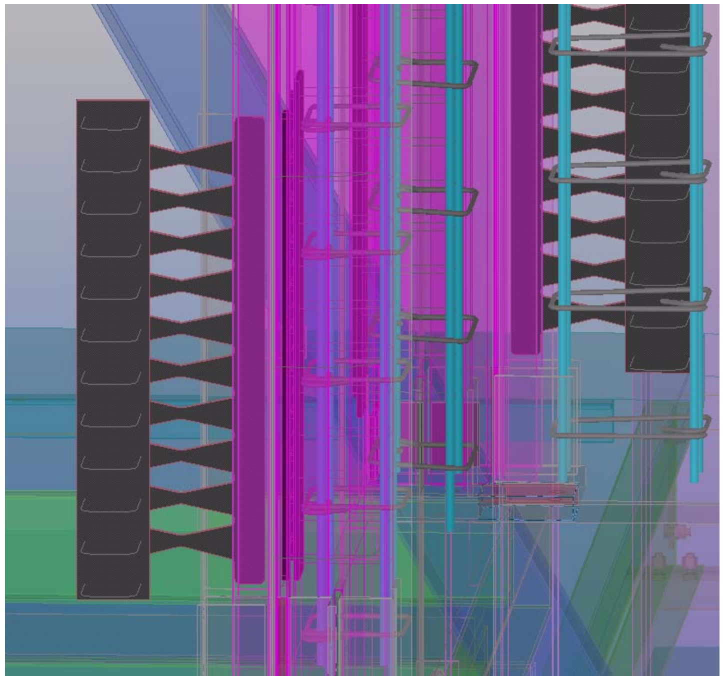


Figure 30. Butterfly plate that attaches CIP walls to steel columns (BIM model courtesy of GPLA Inc., 8/7/08)

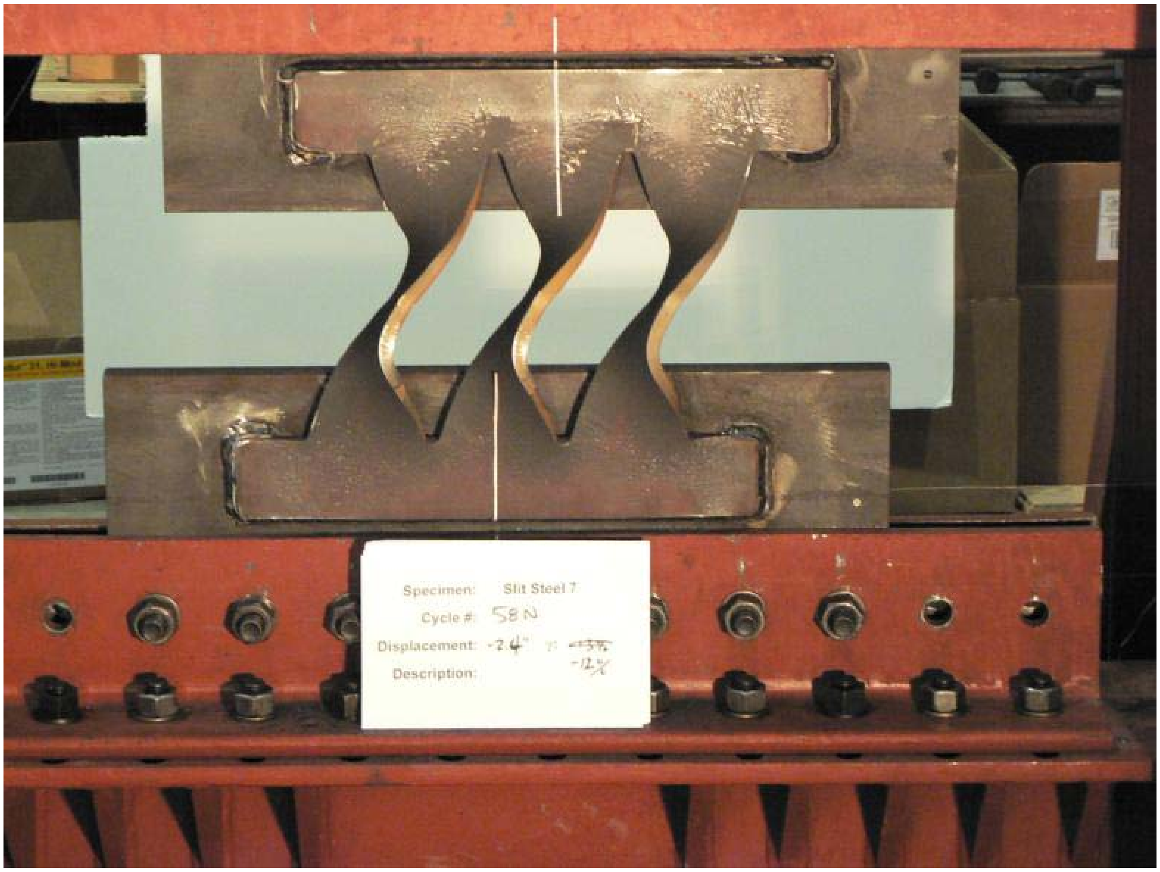


Figure 31. Butterfly plate testing at Stanford University (photograph courtesy of GPLA, Inc. 3/24/08)

In addition to the performance specifications, GPLA needed to meet constructability criteria. The owner pushed prefabrication, so the design team made conscious efforts to design the structure to accommodate it. The general contractor provided insights about constructability, specifically related to rebar fabrication and placement, since the rebar subcontractor was not hired until most of the rebar was designed (Luth 2006). The general contractor's comments were helpful; however, Greg stated the project would need to be "re-designed twice: once when the subcontractors are hired, and again when construction begins" (Luth 2006). The re-design when construction begins refers to the structural engineer developing rebar details they did not have time or money to develop during design (Luth 2006). Indeed, when the rebar subcontractor was hired at the end of the DD phase, he made suggestions that required some of the design be changed. Nonetheless, input from the general contractor early in DD helped the design team meet constructability criteria.

6.6.2 Use of Tekla Structures During DD

From the project outset, the owner required the use of a 3D model. Their goal was to have a fully integrated model developed that they could use in lieu of the traditional 2D as-built plans (Luth 2008). GPLA elected to use Tekla Structures for modeling, and model every bar in Tekla Structures to meet the owner's expectation of a fully integrated model. When DD began in fall of 2006, Tekla Structures 12.0 required users to detail rebar bar by bar (since then, its capabilities have improved significantly and rebar can be detailed in groups). This required a significant time commitment. John Oliva, the detailer at GPLA, explained that learning Tekla Structures is difficult, but worth the effort; it offers "more control and more detail [than other BIM software]" (Oliva 2006). Greg Luth agrees, "Tekla… offers the freedom to make a custom building" (Luth 2006). Once structural engineers determined a rebar layout, John would take about one week to input the information into Tekla Structures so the model would show rebar details. Tekla was eager to help GPLA on this project, specifically, they helped develop a library for the project that included custom connections and rebar configurations.

Only GPLA elected to use Tekla Structures, the rest of the project team chose different software. For instance, the architect used Revit (Luth 2008). This caused coordination issues with the architect, as their model had an origin that was not based on the project grid the rest of the team used, so the architectural model did not align with other models. This was particularly obvious when working with unusual offsets. For instance, exact locations of structural steel details became difficult to align between Tekla Structures and Revit. The MEP subcontractors each used their own 3D software and integrated their models with the structural and architectural models using NavisWorks (Luth 2008).

Figure 32 shows the Tekla Structures model of the whole project, which includes shear lugs, embeds, and rebar (Figure 30 shows these elements in detail). These objects represent custom components in Tekla Structures. They could not be rendered in Revit because Revit could not show shapes from outside its database. This led to difficulty in coordination because custom components were often placed in the most congested areas, and the architects were unable to see them in their model.

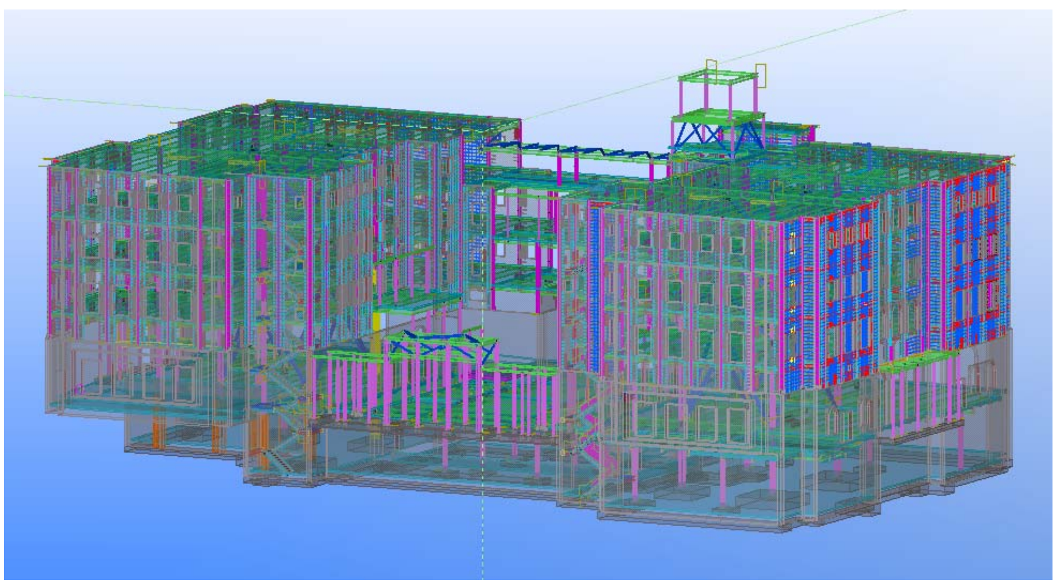


Figure 32. Structural model of the USC project (model generated with Tekla Structures 13.1, courtesy of GPLA, Inc., 8/7/08)

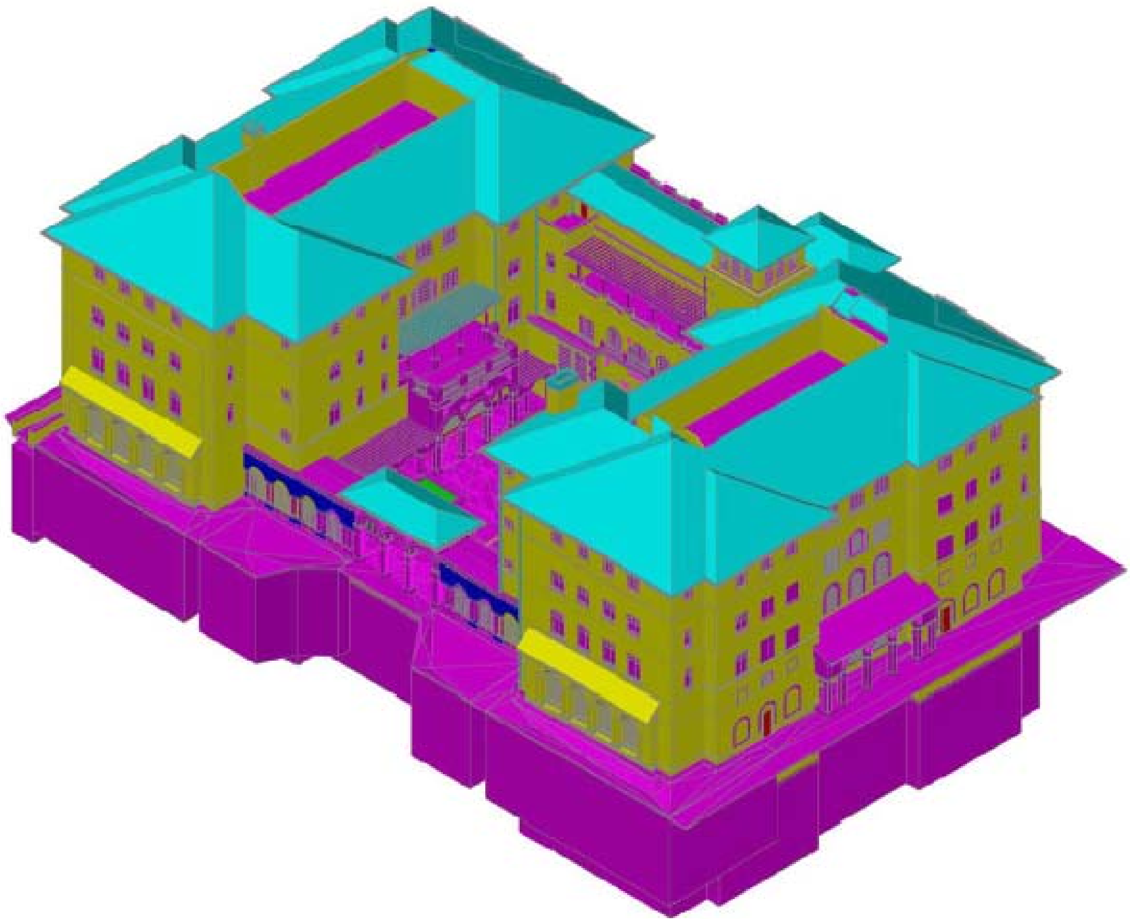


Figure 33. Architectural Revit model of the USC project (Luth 2008)

6.7 CONSTRUCTION DOCUMENTS (CD) PHASE OF THE PROJECT

Once DD is complete, the project moves into the Construction Documents (CD) phase. During CD, the construction manager, in cooperation with the design team, develops a construction schedule. The design team integrates the MEP work and completes clash detection (based on the DD drawings), and the structural engineer finishes rebar detailing to the extent possible given time, project requirements, perceived need, and funds available. The general contractor and subcontractors provide a constructability review for the design team. They may submit RFIs to the design team in the course of this review.

On this project, the owner hired subcontractors in time for them to make contributions to the design team. Thus, CD included collaboration between GPLA and CMC Fontana (the rebar subcontractor). Moreover, it included integration of the design and construction team's BIM models. The contract structure facilitated this integration, as it required BIM modeling.

6.7.1 COLLABORATIVE REBAR DESIGN

As Greg Luth predicted, GPLA re-designed some of the rebar once the owner hired CMC Fontana (Fontana) as the rebar subcontractor. At that time, the project design was about 75% complete (Stowers 2008). Fontana and GPLA had many meetings during CD to develop prefabrication details and schedules. Further, the GC expressed willingness to let GPLA and Fontana speak directly to one another, so they coordinated rebar details over the phone in some cases. Fontana could call GPLA, ask a question, have it answered, and then follow-up with a confirming RFI. This direct collaboration during CD produced a rebar design that was easier to place than the original design would have been. By contrast to this situation, both GPLA and Fontana report having worked with GCs that prefer to mediate communication between the design and construction team, which can cause slow and potentially unreliable relay of information. Both GPLA and Fontana thought the open lines of communication between the two companies created a better project environment (Oliva 2006; Stowers 2008).

Fontana suggested changes to the original design during value engineering. One such change was to focus on facilitating easier rebar placement rather than minimizing rebar weight. GPLA originally designed a structure with minimal rebar weight, but this reduced constructability because too many small bars needed to be placed. GPLA and Fontana added rebar tonnage, but reduced the number of bars, thereby decreasing congestion and improving constructability. Tonnage was also added to accommodate the arches (Figure

29) with straight bars rather than bent ones. The straight bars lent stability to rebar cages during transportation, and made them easier to place. Furthermore, it was difficult to know exactly where cutouts would be in advance, so Fontana suggested straight bars be left in prefabricated assemblies and cut out onsite once the rebar was placed and exact locations were known (Stowers 2008).

Later in the CD phase, Fontana's rebar foreman, Robert Pollock, made suggestions to "improve efficiency on site" (Pollock 2007). For instance, he suggested using uni-ties (Figure 34) as stirrups for corners, rather than using multiple single ties, to reduce congestion on site. A uni-tie is a single piece of rebar with multiple bends that is bent with a machine at the Fontana fabrication shop (Figure 34 shows a uni-tie with Robert Pollock pointing to one of these bends). The tie is a single piece that slips over longitudinal bars. Without it, multiple stirrups would need to be placed individually. For instance, the uni-tie in Figure 34 would be replaced by three individual ties (called out as [1], [2], and [3] on Figure 34). Because the ties overlap (note the corner that shows the intersection of three stirrups), they also take up more space along the wall length than a uni-tie. That is, if three separate stirrups were placed, they would take up 3 bar diameters of space along the longitudinal steel (on the order of 1.5 inches). However, the uni-tie saves some of this space, using only two bar diameters of space on the longitudinal wall (called out as [4] on Figure 34), thus reducing congestion.

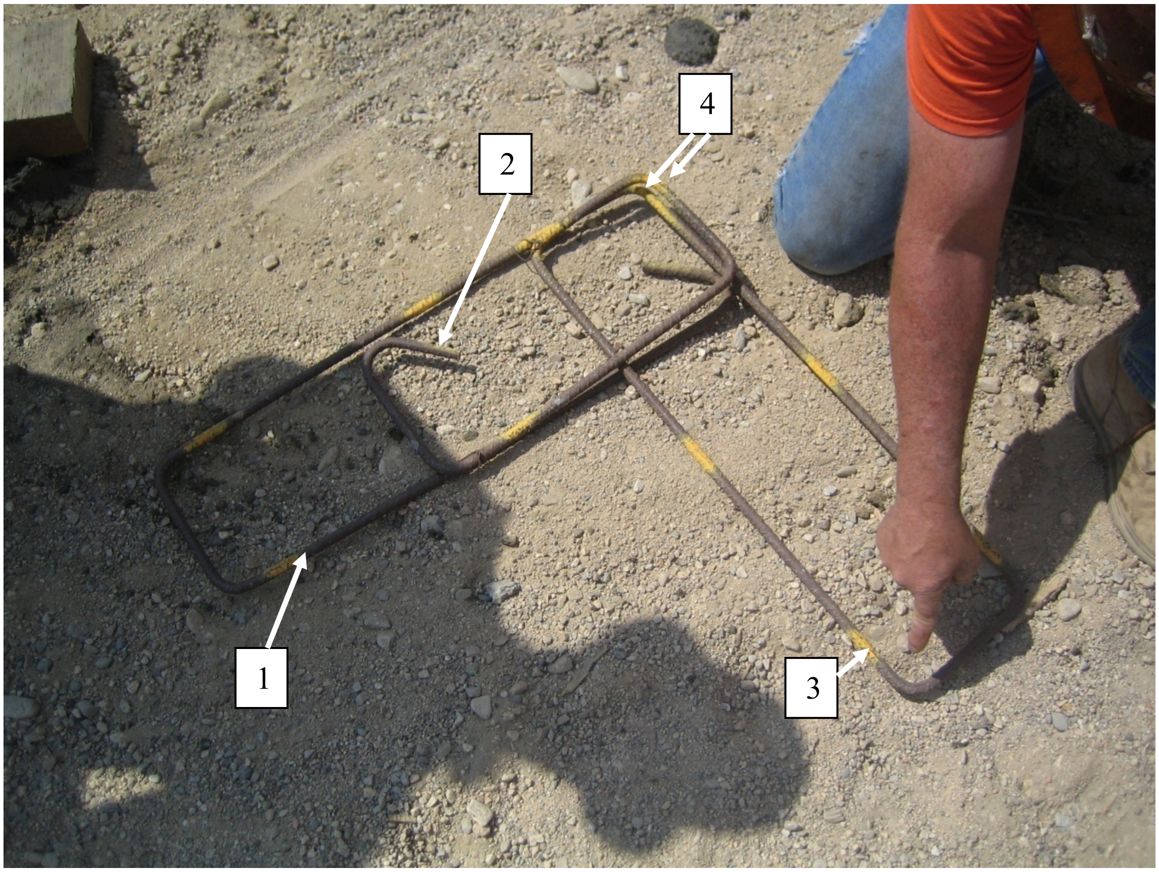


Figure 34. Uni-tie used to reinforce wall corners on the USC site (photograph taken by Kristen Parrish, 7/9/07)

6.7.2 FONTANA'S CHOICE OF SOFTWARE

Fontana used RebarCAD and AutoCAD to detail rebar for this project. They also used Tekla software on a limited basis, namely the Tekla Viewer to look at the congested areas of the model and develop details that would reduce congestion if possible. Detailers at Fontana were accustomed to using RebarCAD but new to Tekla software, so they were able to detail the job and generate placing drawings more quickly than they would have using Tekla Structures. Detailing speed is key to the business of a rebar fabricator-placer (like Fontana), so they only switch software if a compelling business case exists (Stowers 2008). At the time this project was designed, Fontana did not feel the capabilities of Tekla Structures warranted the investment of time required to train their detailers would require. Further, to use Tekla Structures most efficiently, Fontana would need to develop a library of custom components, e.g., for uni-ties. However, Fontana did not have sufficient time to develop this library and detail the job (other subcontractors were unable to develop the necessary libraries in the time allotted as well). Finally, RebarCAD outputs drawings that are compatible with the fabrication shop and Soulé Software (accounting and estimating software), so fabrication and accounting can be done automatically (Stowers 2008).

GPLA suggested Fontana use Tekla Structures for detailing directly to take advantage of the details already in the model. GPLA felt they could eliminate work for Fontana because the BIM model had accurate quantities for takeoff and specific details (rather than the "typical details" commonly shown on structural drawings). That is, John Oliva detailed the Tekla Structures model bar by bar, so he was confident every piece of rebar that needed to be placed was modeled. However, Fontana expressed concern about using the Tekla Structures model directly. They were not familiar with the software, and worried the bar lists may not be accurate. Further, the Tekla Structures details did not communicate with the machine shop or accounting software, so Fontana reasoned they needed to detail the job anyway to develop fabrication and accounting details. Indeed, quantities output by Tekla Structures and those used for the job were within 5% (Soulé 2008). Differences in quantities were attributable to extra bars used for fabrication or transportation not shown in the model (e.g., the straight bars in the arches discussed above).

6.7.3 COLLABORATION NECESSARY FOR A SUCCESSFUL PROJECT

GPLA designed the building to be erected with a wall-then-floor construction sequence. However, they included temporary bracing in the structural plans to add flexibility for the GC to dictate another sequence if that made more sense for the project schedule. Indeed, "everything changed at the pre-bid conference" (Luth 2008). Once the GC was hired, the superintendent began to work with GPLA to develop a wall-and-floor construction sequence. It required the temporary bracing, so the structural steel subcontractor needed to make arrangements to deliver and place that steel.

GPLA also offered flexibility in rebar placement. They provided two structurally-acceptable corner details for the project and let Fontana decide which one to construct based on their capabilities. Greg stated, "I always thought the best way do a project was to really specify everything. However, this project has taught me it makes sense to be flexible" (Luth 2008).

The design and construction team needed to work together on this project for it to be successful, because the shear rocking wall system had never been built before. Thus, a "typical detail" did not exist. In fact, nothing about the job was "typical" (Luth 2008). Thus, GPLA suggested a mockup be built to understand both the construction product and process better. Figure 35 shows the mockup: it had straight bars in the archway that needed to be cut out. Also note the tight tolerance between the rebar and the concrete embeds. After the mockup, both the construction schedule and the rebar placement method changed. When developing the construction schedule, GPLA and the GC assumed one cage would be taken on a truck from Fontana's shop in Etiwanda, CA to the site in Los Angeles, CA (a 49.7 mile trip) in the morning and another one in the afternoon, totaling two cages per day. No one on the design or construction team had worked with this structural system before (since it was custom-made for this project!), so the two cages per day assumption seemed reasonable and conservative. However, five cages fit on a truck, and all of them were placed in 3 hours during the mockup construction. So, the rate changed from 2 cages per day to 10 cages per day. Moreover, the assemblies themselves needed to be adjusted, because the assembly jambs hit the embeds during mockup construction. The team was pleased to see how quickly Fontana could install the rebar cages. However, deviation from plan, even when activities proceed ahead of schedule, can be problematic on a construction site. For instance, structural steel erection may not be able to match the rebar placement pace, so the rebar crew may be forced to stop and start, despite theoretically being able to place continuously. Finally, the construction team realized the butterfly plates were heavier than expected, so a forklift was brought in to place them.

Figure 35. Mockup of a concrete panel for the USC project (photograph from Luth (2008)

6.8 CONSTRUCTION AND ON-SITE ADMINISTRATION PHASE OF THE PROJECT

The Onsite Administration phase of the project involves RFI submission and answers, day-to-day operations onsite, and execution of the construction activities and schedule. The USC project is in this phase at the time of this publication (May 2009). Rebar placement is progressing at a rate of 10 cages per day. “In this phase,” the job assistant superintendent mentioned, “it is critical [that] the rebar foreman have a good relationship with the shop” (Fisher 2007) so material deliveries and placement activities proceed as scheduled. Rebar connects the structural steel to the concrete columns, so it literally holds the entire structural system together (Luth 2008), so it needs to be delivered and placed on time to keep the schedule on track. Robert Pollock also explained the shop works about 24 hours ahead of the site, so if a change in delivery is necessary, he needs to request it more than 24 hours in advance. Otherwise, the shop may be unable to get the rebar to the site in time (Pollock 2007). Onsite administration concerning rebar for this project focuses on ensuring rebar arrives to the site on time and can be placed immediately. Figure 36 shows a preassembled rebar cage being picked right off the truck and flown into place.

6.9 LESSONS LEARNED

The USC project illustrates an innovative rebar design product and process. Throughout the project, the team learned how to work individually and together with BIM models as well as how to design and construct the shear rocking wall system. They learned the importance of early collaboration for both modeling and design: fully integrated BIM models take time to develop and buildable designs require constructability reviews from subcontractors.

Figure 36. Placing a prefabricated rebar panel (Figure 8 in Luth et al. 2008)

6.9.1 Fully Integrated BIM Models take Time to Develop

The expectations of the project team for the BIM model were ambitious from the start. Beyond ambitious, the expectations were "nearly infeasible" because people wanted the model to show many different things, which required a very detailed BIM model (Luth 2008). A BIM model with this much detail requires a lot of time to develop. The subcontractors, for instance, did not have time to learn new software, develop libraries, and detail the project in the time they were allotted.

Subcontractors modeled their work in their own software programs, and these models were integrated with the architectural and structural models in NavisWorks once a week. For future projects, subs would need more time to develop libraries to integrate with architectural and structural models directly, rather than through NavisWorks. That is, the team could develop a single model in one software, view the model in real time, and pre-empt clashes between trades. They could also use the single model for estimating and understanding congestion, as all quantities and objects could be shown in this single model. Coordination between different software programs made it difficult to see all project details, posing a challenge to a fully-integrated model. Better interoperability between software programs would make models easier to integrate and thus more useful.

6.9.2 The BIM Process Changes How Design Teams Work

Though the owner's project manager required BIM be used during design, he also required 2D drawings be developed in parallel with the 3D model. These drawings were necessary, because in some cases, they showed more detail than the model, due to software limitations (Luth 2008). For example, some of the architectural details were not shown in the architect's model, but were shown on 2D drawings, requiring the construction team use 2D drawings (at least for architectural details). However, if BIM models show all the details necessary for construction, they could potentially replace 2D drawings. This change would require engineers and builders alike to change their processes to fully take advantage of BIM models. Engineers need to fully detail the model, rather than provide "typical details" in 2D drawings. Builders need access to the model, and must build to exact specifications insofar as possible with tolerances. In an e-mail dated March 5, 2009, Greg Luth discussed how BIM is changing the design and construction process (Luth 2009):

> We and multiple subcontractors are now working on the same web-based design/detailing model at the same time on multiple projects for multiple owners and clients in a variety of contractual relationships. We have only ONE structural model on each of these projects. The reason for this is that the "model" is just a database. It is not embedded in a graphics package. We have successfully argued that for practical reasons the contractor should and will use the model as his primary source of information. The practical reasons are that once we put all the detail into the model, that's where "god lives" and there is no way to extract that information and present it clearly and comprehensively in a set of 2D conceptual drawings or in a set of 2D literal drawings.
>
> We are linking the construction trailers to the "live" model. On every project there are job boxes for tools and kiosks for reference drawings in the building that is under construction. These are used by the foremen and crew that are actually doing the work. We are on track to put flat screen monitors in the kiosks with a wireless link to the ONE model. It will not be long before there are links between the PDA's that will be an indispensable addition to the journeyman's tool belt and the ONE model.
>
> We also know for a fact that it takes twice as long to extract the pathetically ineffective drawings from the model as it does to actually model 100% of the detail, even throwing in the time it takes to coordinate with the superintendents and foremen that are going to construct the building. The thing that has finally made the 3D model useful is that we actually put all the construction details into it.
>
> We have clearly crossed a significant bridge and I do not foresee this ever going back to the way it was.

> In the future, talk of a "construction" model and a "design" model will be considered just silly.

Finally, BIM software itself keeps changing, and must continue to change, which could further change the design and construction process. For instance, Tekla helped GPLA with detailing throughout this project. As the project progressed, Tekla developed a better sense of what their customers would need to effectively detail cast-in-place concrete projects. Thus, they "came a long way" from the beginning of the project (Luth 2008). One example of this progress is Tekla Structures moving from a model where rebar had to be input bar-by-bar (Tekla Structures 12.0) to a model where bars were input in groups as appropriate to reinforce a concrete object (Tekla Structures 14.0). Similarly, Revit, which did not have rebar modeling capabilities when the project began, now has rebar detailing capabilities. As software continues to progress, the design and construction process can capture more knowledge to increase project-to-project learning.

BIM software as it exists today needs to change to accommodate the tolerances inherent to construction materials and assemblies. BIM models assume objects have exact dimensions, and do not account for variability in the real world. In congested areas, a construction tolerance may be the difference in an element fitting or not. People currently do not annotate their BIM models to express tolerances. Designers and contractors need to be aware of the assumptions used in models so they remain attentive to congestion. Designers may need to keep tolerance in mind in design and leave room for tolerance in the model. Similarly, builders may need to change placement practices, as placing from a model requires precision that may not be necessary when working from 2D drawings. Indeed, placing exactly according to the model requires discipline, whether in congested areas or not.

6.9.3 SUBCONTRACTORS NEED TO BE INCLUDED IN DD

Greg Luth stated, "it's useless to detail all the rebar without Robert [Pollock], because he has a huge stake in the project" (Luth 2008). GPLA worked to develop trust with Robert Pollock so he could contribute to design, and thus have confidence he can do what it takes to build it. He informed GPLA about constructability and offer suggestions to improve it. His suggestion to use uni-ties, for instance, reflects his unique knowledge of the rebar placement process. GPLA welcomed suggestions like these, and stated it would be beneficial to have this input earlier so they could design rebar the first time to accommodate constructability concerns.

6.9.4 MOCKUPS HELP UNDERSTAND INNOVATIVE PRODUCTS

The USC project featured a new structural system, the shear rocking wall. Since none of the team members had ever worked with it before, a "typical" detail did not exist (Luth 2008). Thus, the team built a mockup to learn how the shear rocking wall would fit together (even *if* it would fit together!). They learned they could place rebar faster than expected as a result of the mockup. Further, the rebar placers learned in the course of building the mockup how to actually place panels and they were able to give the detailers feedback about necessary changes (e.g., moving jambs of the cages to avoid intersection with embeds).

6.10 CONCLUSIONS

The USC School of Cinematic Arts Complex Expansion project represents an innovative design product and process. From a product perspective, the shear rocking wall system is a first. Based on the owner's "enabling details," including the stucco façade and the need for prefabricated elements, the design team explored multiple alternatives before selecting a CIP wall-steel column system. They then worked to develop one that met the owner's performance requirements, which yielded the shear rocking wall system. They tested the system to understand its performance characteristics and built a mockup to understand how it fit together. Schedule and methods needed to be modified after the mockup. In future projects, it may be worth exploring how flexible schedule and methods are relative to these changes. Rebar was placed ahead of schedule, and the steel contractor was able to accommodate this change, so time was saved. However, unplanned variations (even those that reduce the time to complete a given activity) can disrupt the so-called "parade of trades," (Tommelein et al. 1999) and thus need to be accounted for.

The USC project also illustrates a new process for design and construction, one that focuses on use of BIM models for coordination and integration amongst the various building systems (architectural, structural, MEP, etc.). This project provided opportunities for the team to learn how BIM models can improve the delivery process. They learned model integration is non-trivial and takes time. Further, they learned that the model must include construction details to provide most value for the team. Finally, they learned complexity abounds when new products and processes are introduced at the same time, highlighting the need for education of the project team.

CHAPTER 7. CATHEDRAL HILL HOSPITAL CASE STUDY

7.1 INTRODUCTION

This chapter describes the set-based design efforts on the Cathedral Hill Hospital (CHH) project. It presents two decisions made using set-based design out of many such made on this project: (1) the selection of the structural system and (2) the selection of a landscape architect and green roof consultant. It then compares and contrasts how CHH decision-making teams made these decisions as the set-based design process evolved on the project. One project team used set-based design to develop an innovative and cost-effective structural system that may set precedent for other medical facilities to be constructed in seismically active zones. Another project team used set-based design, in conjunction with A3 reports and CBA, to select a landscape architect and green roof consultant. These examples illustrate the evolution of the set-based design and decision-making processes for the project and the benefits of using A3 reports and CBA.

Lean project production theory describes projects as "networks of commitments" (Macomber 2005) and design as a social process (Bucciarelli 2003). These views purport that effective communication is required for successful project management. An A3 report is a tool to support effective communication, synthesizing information necessary for teams to develop a shared understanding of the project (Shook 2008; Sobek II and Smalley 2008). A3s can guide so-called 'priority conversations' (e.g., Mikati et al. 2007), explaining breakdowns or current situations as appropriate. A3s may show design alternatives and discussion topics brought to the fore in design conversations; they are not a substitute for these conversations.

7.2 COMPANY AND PROJECT BACKGROUND

The California Pacific Medical Center's (CPMC) Cathedral Hill Hospital project is a new 555-bed hospital in San Francisco, California, budgeted at $1.7 billion. The hospital is 1,000,000 ft^2 with 555 parking stalls with a total of 13 above and below grade stories. The project is sited on sloping terrain, 6.8 mi from the nearest active earthquake fault. Design of CHH began in 2005 and construction of the project is expected to complete in 2013. The project had been completely designed once before, but cost estimates based on that design exceeded the owner's budget, so the project was stopped. Documents from this first design served as a starting point for the new design team.

CPMC is an affiliate of Sutter Health, a major healthcare provider in Northern California. Sutter Health has shown a commitment to lean practices in its hospital design and delivery processes (Lichtig 2005a) and is managing a portfolio of lean projects (e.g., Mikati et al. 2007). As a part of its lean implementation, Sutter Health encourages project teams to implement the 'Five Big Ideas' (Macomber 2005; Mikati et al. 2007):
(1) Collaborate, Really Collaborate; (2) Manage Projects as a Network of Commitments; (3) Increase the Relatedness of the Project Participants; (4) Tightly Couple Learning with Action; and (5) Optimize the Project as the Whole." These ideas, implemented using a relational contract called the Integrated Form of Agreement (IFOA) (Lichtig 2005a; 2005b; 2006), have fostered an environment of collaboration and innovation on the project.

The CHH Integrated Project Delivery (IPD) team includes CPMC (owner), SmithGroup (architect), Herrero/Boldt (construction manager and lean process integrator), Degenkolb Engineers (structural engineer), Herrick (steel fabricator), Dowco (steel detailer), Dynamic Isolation Systems (supplier of viscous damping walls), Pankow (concrete subcontractor), Southland Industries (mechanical subcontractor), and other companies.

The Integrated Form of Agreement (IFOA) (Lichtig 2006) requires the IPD Team subdivide into Cluster Groups. “Cluster Groups for this project included structural, mechanical, electrical and plumbing, exterior skin (architectural enclosure), interiors, project requirements, site work, and conveying systems” (Ballard and Rybkowski 2009). Cluster Groups take responsibility for their piece of the project, i.e., the Structural Cluster Group is responsible for the structural systems, the Mechanical Cluster Group is responsible for the mechanical systems, etc. However, a representative from a single company may be a member of multiple Cluster Groups, to ensure Cluster Groups do not act “in a vacuum.” Each Cluster Group also has a target budget to meet (Ballard and Rybkowski 2009), and dual membership may support budget reallocation (e.g., the Mechanical Cluster Group could donate some of their budget to the Exterior Skin Cluster Group).

The Core Group, a group of project stakeholders contractually responsible for the functioning and operation of the project, make project-level decisions, such as the two decisions described in this chapter. They require that all Cluster Groups submit information for project-level decisions in A3s. Cluster Groups also submit A3s for decisions that require input from the user group and those affecting operation.

7.3 STRUCTURAL SYSTEM SELECTION

Structural system selection during the design phase of a hospital project is no small task. The system must meet many requirements imposed by owners, architects, engineers, and others, most notably in the case studied: California's Office of Statewide Health Planning and Development (OSHPD) (http://www.oshpd.ca.gov/). OSHPD serves the state in the process of building permitting by verifying that hospital design and construction comply with its legislative framework for seismic safety. The Hospital Facilities Seismic Safety Act, SB 1953 (1994) (California Seismic Safety Commission 2001), requires that acute care facilities remain functional during and following an earthquake. In order to meet these stringent requirements, owners, architects, structural engineers, contractors, and other specialists alike have been forced to re-think their design and construction strategies. This chapter reports on how CHH's Structural Cluster Group responded to this challenge by developing an innovative alternative solution on their project using set-based design.

An accepted structural design solution to achieve seismic performance in California has been to use base-isolated structural systems (e.g., http://nisee.berkeley.edu/lessons/kelly.html). These systems tend to be cost effective on hospitals, but not necessarily on all. For example, on sites with a steep grade, as is the case for CHH, it would be difficult to build the moat around the facility as needed to allow a base-isolated structure to displace horizontally. The IPD team used set-based design to explore alternative structural systems. The Structural Cluster Group mapped the structural system design space, and then the IPD team evaluated the alternatives and made a selection.

7.3.1 Set Definition—Map Design Spaces for the Structural System

During Schematic Design (SD) (Figure 3), the IPD team selected the building material and structural system. During Design Development (DD) (Figure 3), they decided on structural system details and preliminary mechanical, electrical, and plumbing (MEP) layouts.

The “first step” in set-based design maps the design spaces to define (1) the decision(s) to be made and (2) the available design alternatives (Sobek II et al. 1999). As a project progresses, the sets examined at each phase become increasingly more detailed. Clearly articulating the level of detail necessary to define alternatives at a given phase of design requires open communication, establishing the factors and criteria each stakeholder considers relevant, and understanding of the competencies each stakeholder can contribute. Lack of clarity on these is an obstacle to set-based design. Each IPD team member must understand not only what is asked, but also the purpose at hand, given requests for handoffs made by others on the IPD team. This allows the IPD to make reliable promises, that is, to make commitments and fulfill them (Macomber and Howell 2003; Winograd 1987). Too much detail too early forces unrealistic and undesirable commitment, while too little detail early in the process may result in otherwise avoidable rework.

7.3.1.1 Problem of Too Much Detail when Mapping the Design Space

The difficulty of defining the level of detail needed for reliable promises to be made is illustrated by conversations held during IPD team meetings discussing (1) openings in walls and (2) the exterior skin system.

Example 1 - Wall Penetrations: In order to define the structural system details, the structural engineer requested the location of wall openings required by the MEP team. In the spirit of collaboration, the MEP team started to calculate their penetrations; they thought that locations of openings down to ±4 inches had been asked for. This was a difficult if not an impossible task to do so early in the design process because other system parameters had not yet been pinned down. That is, the MEP team and structural engineer came to a roadblock because the design was too uncertain for the MEP team to confidently give the structural engineer the location of all of the wall openings. When the MEP team communicated their difficulty in responding to this request, the structural engineer clarified what had not yet been made explicit, namely that only locations of openings on the order of 8 ft × 8 ft or larger were of consequence to develop structural system details. With this clarification and information from the MEP team, the set definition proceeded for structural system detailing.

Example 2 - Skin of the Structure: The weight of the exterior skin affects the loads and demands on structural elements at the periphery of the building. In order to develop structural system details, the structural engineer asked the architect for this information, but at that time the skin weight was still uncertain. This roadblock was resolved when the structural engineer clarified that the exact weight was not needed, but rather only whether the skin was 'heavy' vs. 'light,' i.e., on the order of 25 lb/ft^2 vs. 75 lb/ft^2. The architect's clarification that the skin would not be of the heavier variety, allowed the structural engineer to continue with detailing while the architect could postpone commitment to a particular skin type and manufacturer.

Lessons Learned: In both of these examples, one party assumed that more detail (precise information) was needed than was necessary for the other party or typically available in that phase of the design process. Such uncertainty supports the use of a set-based design approach, as commitment to specific values for wall openings and skin weights can be postponed. Designers must learn to articulate what they really need for their own work and what they need to request from (or give to) others with reasons why, in accordance with their modeling, analysis, and decision-making capabilities, while recognizing that their and others' needs change with different project phases. Simply stated, foot-level details may be appropriate in early phases whereas inch-level details may be appropriate later. Degrees of required specificity must be articulated not only for geometric but also for non-geometric design attributes.

7.3.1.2 Problem of Too Little Detail when Mapping the Design Space

In some cases, trying to provide too much detail relatively early can impede mapping the design space. In other cases, providing too little detail can impede it. The IPD team's discussion about beam layout illustrates this.

Example – Beam Layout: It is important to resolve the choices of floor-system beam depth and spacing early in design since they impact how ductwork gets laid out. The structural engineer and MEP team wanted to coordinate their parameter choices so that the ducts could fit in-between the beams and girders, thus saving floor height (no additional vertical space needed to fit ducts). The structural engineer and MEP team coordinated their work by agreeing upon the maximum depth of beams and girders.

However, the team initially failed to discuss another parameter: beam orientation. The MEP team assumed that the beams would be laid out perpendicular to the external wall so that ducts could run from the building interior through the length of the patient rooms, using the space in between them. In contrast, the structural engineer assumed that beams would run parallel to the external wall. The structural engineer took it for granted that the MEP team would intuitively opt for the orientation they had assumed, so neither party specified up front what their assumption was. Here, the set parameter specification should have included beam depth, spacing, and orientation. The team did not realize that all three were required at this stage of design, until they discovered the conflict later.

Lessons Learned: Both parties specified less than they actually required at this stage in the process and this miscommunication resulted in negative iteration (Ballard 2000c) to find a satisfactory design. This miscommunication illustrates the importance of defining set parameters properly and exploring them by obtaining input from other project participants before proceeding with decisions. If the two sets' definitions had included the variable 'orientation,' options could have been evaluated and decided on without requiring rework.

7.3.1.3 Structural System Alternatives that make up the Design Space

Figure 37 shows four structural system alternatives the IPD team considered. Each system controls inter-story drift using a different mechanism. The moment frame relies on the stiffness of its columns and girders, as well as the strength of the connections between these members, to resist lateral deflections. The piston-damper system provides supplemental damping to the moment frame, which allows for energy dissipation and resists displacement like a braced frame by concentrating large axial loads through the connection points. The viscous damping wall (Figure 37 and Figure 38) resists displacement by shearing and distributes forces along the entire wall length via the connections to the top and bottom of beams. The base isolation system reduces inter-story drift by concentrating large displacements at the base level; accommodating such displacements requires a special moat around the perimeter of the building.

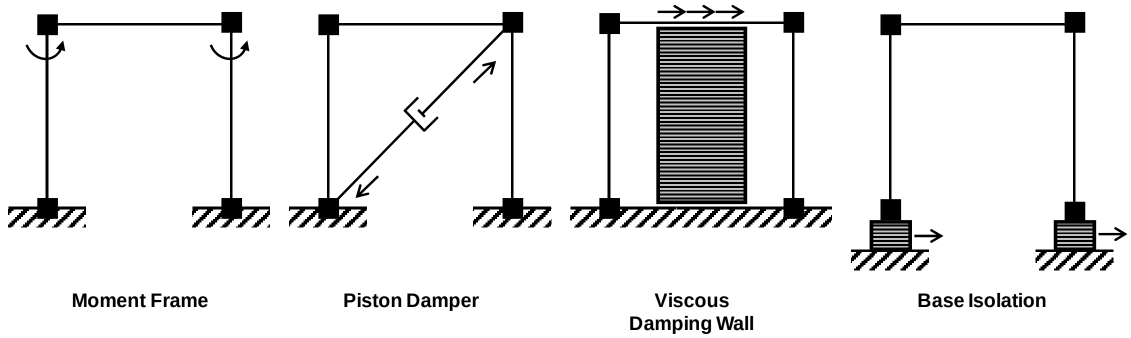


Figure 37. Options for Structural Systems (Figure 2 in Parrish et al. 2008a)

Figure 38. Viscous Damping Wall Model (Photograph taken by John-Michael Wong 2/25/08, Figure 1 in Parrish et al. 2008a)

7.3.2 EVALUATING AND NARROWING THE SET OF STRUCTURAL SYSTEM ALTERNATIVES

Figure 39 illustrates the narrowing of the set of alternative structural systems. Initially, the Structural Cluster Group considered four systems. As must and 'want' criteria were applied, and attributes of alternatives discussed, the Structural Cluster Group eliminated alternatives. In the end, only the viscous damping wall met the lateral force resistance criteria and budget.

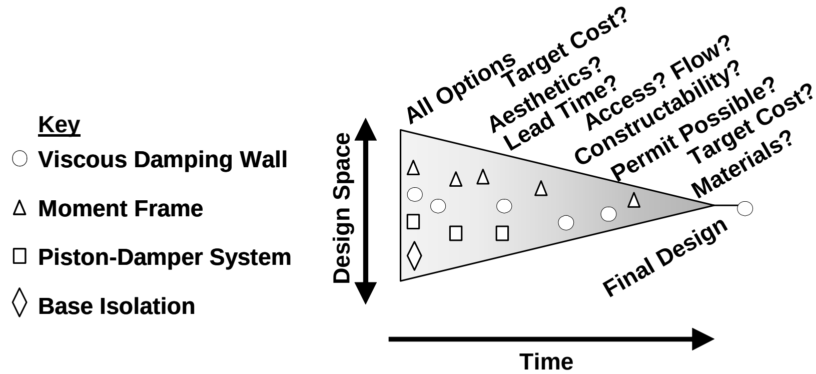


Figure 39. Set Narrowing Scheme for the Structural System Selection (Figure 3 in Parrish et al. 2008a)

A base isolation system was the initial choice (Morgan 2007; Naeim and Kelly 1999; Tuholski et al. 2009), as this was the "received tradition" for hospital design in California. That is, designers may consider base isolation systems to be the only way to deliver California hospitals that meet legislative requirements about seismic safety. However, due to the cost associated with building and maintaining the displacement moat, the team decided not to pursue this alternative. CHH would need a 30-inch moat around the building and excavating such a moat on a sloping terrain, as is the case on this project, is a challenge. This moat would require complicated stepping, special piping detailing, breakaway sidewalks, and special loading docks to accommodate large trucks, thereby imposing challenges to other building system designs. The building with a base isolation system would be taller than the other alternatives and require special 2-story trusses to accommodate the mid-height mechanical floor.

The moment frame alternative required about 50%-75% more steel for stiffness than, e.g., viscous damping walls would, in order to meet inter-story drift limits.

As an alternative, the Structural Cluster Group explored viscous damping walls. These walls are full-story height and are bolted to steel beams on the top and at the bottom. The viscous material inside the wall is polyisobutylene (Aseismic Device Company Ltd. 2008). In Japan, such walls have been used in high rise buildings, but in the United States, their use on CHH will be a first. This structural system does not require a displacement moat. Furthermore, a viscous damping wall is self-contained inside a wall. The structural engineer designed CHH such that the viscous damping walls would be placed perpendicular to walls with MEP and architectural features, thereby reducing the likelihood of clashes between them. The viscous damping wall is also considerably less expensive than the other alternatives, saving about 1% of the total project cost. Furthermore, after a seismic event, the system allows for bolt replacement, if necessary, whereas the structural steel frame is expected to remain elastic and therefore would not need to be replaced. The Structural Cluster Group favored this alternative for its structural properties and because its expected repair costs are lower than those of most other alternatives.

During SD, the IPD team compared structural systems in a matrix on a whiteboard (Love 2008). They discarded the base isolation system from consideration, due to the difficulty with the moat. They evaluated the remaining systems in terms of their structural quantities (including steel framing weight, concrete mat foundation thickness, quantities of viscous damping devices, etc.), expected seismic performance (drifts and accelerations), and expected shaking at different locations in the building for the design level earthquake event. Table 23 shows the advantages of each alternative considered.

Table 23. Advantages of a moment frame and a moment frame with dampers (adapted from information in CHH IPD Team 2007)

Advantages of the Moment Frame	Advantages of the a Moment Frame with Dampers
328 less dampers than the 328 dampers required for the piston-damper or viscous damping wall	Requires about 15 lb/ft^2 less total steel frame weight than 37 lb/ft^2 (moment frame) ~.5% less drift than the 1.5% (moment frame) ~ 40% – 60% less floor acceleration at levels of interest than the moment frame

Based on their comparison, the IPD team selected a moment frame with dampers, specifically the viscous damping wall. It and the piston-damper system require less total steel frame weight (on the order of 15 lb/ft^2 less) than the conventional moment frame. All three alternatives require the same concrete mat foundation thickness (thus, no alternative has an advantage). The piston-damper and viscous damping wall alternatives allow approximately 1% drift; the moment frame allows approximately 1.5% drift. Finally, in terms of expected shaking, the piston-damper and viscous damping wall alternatives experienced lower floor accelerations than the moment frame at all locations of interest (CHH IPD Team 2007). Ultimately, the IPD team favored the viscous damping wall over the piston-damper based on cost savings and relative ease of repair.

7.3.3 Testing and Analysis of the Viscous Damping Walls

The viscous damping walls were developed by Sumitomo in Japan (Aseismic Device Company Ltd. 2008). For this project the walls will be fabricated by Dynamic Isolation

Systems in the United States and prototypes will be tested for structural performance at the University of California, San Diego. CHH has three different floor heights for which three different heights of walls need to be fabricated: 14 ft, 16 ft, and 17 ft. To limit the cost of testing, the structural engineer chose to standardize the widths of the walls to be used: 7 ft, 8 ft, and 8.5 ft for the 14 ft, 16 ft, and 17 ft walls, respectively. The structural engineers designed the frame to remain mostly elastic; therefore its restoring force is expected to re-center it after an earthquake.

Use of innovations like the viscous damping wall requires the structural engineers to perform an advanced nonlinear analysis in order to justify the system's ability to meet structural performance goals. This innovation is not part of the 83 seismic force-resisting systems for which ASCE 7-05 gives design coefficients (ASCE 2005). Thus, the structural engineers required design time to resolve modeling issues and ensure the solution will meet all project-specific requirements. The owner encouraged the structural engineers to carry out additional analysis by paying them on a time-and-materials basis. Team members who are not rewarded for the additional time they may have to invest in order to develop innovations may be more likely to stick to 'conventional' systems that may not be as desirable in terms of meeting the capabilities and preferences of the entire team. By including everyone on the team in the IFOA and rewarding project teams for innovation while having them share risks, they can develop more desirable system solutions for the owner.

7.3.4 PERMITTING

The process for permitting this project is also innovative because of the consideration OSHPD is giving to the use of the new structural system and their adoption of phased plan review. The IPD team sent a preliminary design submittal to OSHPD in order to get buy-in and concept approval on basic issues. This permit submittal contains mostly structural design information such as design criteria, gravity system, and loading.

It is better to negotiate changes during design than during construction, because the process for making changes to construction drawings, especially once field work has begun, could take up to two weeks for a minor design change and possibly months if not years if drawings need to be re-submitted to OSHPD for permitting. A long turn-around time for permitting results in an unpredictable schedule and extends the project duration. Problems during construction often involve differences between 'typical' details and the real conditions in the field (another example of the too-little-detail problem). The owner entered into the IFOA with the construction team during the design phase of the CHH project, allowing for coordination between designers and builders *before* permitting, thereby reducing the need to make changes or document specific details during construction, and thus avoiding delays due to re-submitting drawings to OSHPD.

7.4 SELECTION OF A LANDSCAPE ARCHITECT AND GREEN ROOF CONSULTANT

At the time the IPD team selected a structural system in July 2007, they were not yet using A3 reports on a regular basis. They did not yet have a formal decision-making system in place, so they evaluated structural system alternatives and selected one based on comparing alternatives relative to specific factors. They compared systems quantitatively when possible. However, the process of comparison was somewhat informal. The IPD team started to adopt the A3 process to capture decision-making rationales on March 7, 2008 (Koga 2008a). They used this process to select a landscape architect and green roof consultant.

7.4.1 Use of A3s on the Cathedral Hill Hospital Project

In order to streamline the decision-making process on CHH and make it more transparent, the Core Group makes project-level decisions. This group consists of David Long (Sutter Health), Geoffrey Nelson (Operations Advisory Committee representative with CPMC), Ralph Marchese (Marchese Co.), Steve Peppler (SmithGroup), Paul Reiser (HerreroBoldt), Lonnie Andrews (Pankow Builders), and Tony Burg (Sutter Health).

The CHH IPD team is experimenting with the development and use of A3s to improve their project's delivery. Managing with A3s represents a major cultural change for the team, so they have tailored Toyota's process to their own organization's need and they are making adjustments to it as they hone their skills. At CHH, IPD team members write A3s to provide information and recommendations for decision-making to the Core Group. In this A3 effort, the IPD team also employs Value Analysis techniques (Miles 1962) are often employed by the team during the A3 effort. HerreroBoldt's Value Manager, John Koga, reviews A3s and then either requests the authors make revisions or passes the A3 on to the Core Group for their review. As the IPD team's A3 writing process evolves, the Core Group is also changing their A3 review process. At the time of this writing, the Core Group is phasing in discussions with the A3 author during their meetings as part of the A3 process. A3s may be revised after first Core Group review to capture new information, re-define the problem or countermeasures, or both.

7.4.2 Landscape Architect and Green Roof Consultant A3 Report

Figure 40 shows the Landscape Architect and Green Roof Consultant A3 report used on CHH. Successive figures (Figure 41 - Figure 45) illustrate the specific components of this A3. The author of this dissertation modified these detailed figures to reflect the new purpose of this A3 (i.e., to serve as an example for this chapter) and the A3 standards implemented at CHH at the time of this writing.

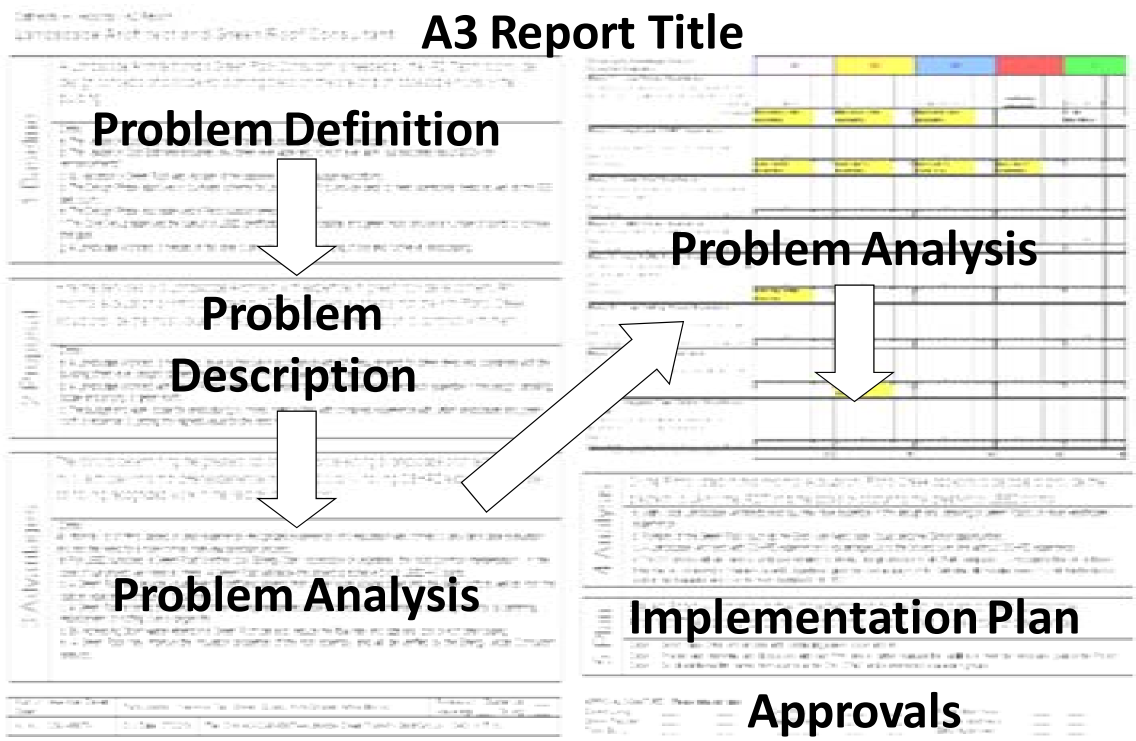


Figure 40. Landscape Architect and Green Roof Consultant A3 illustrates flow of A3s

Figure 41 shows the Baseline section of the A3 report, which provides problem definition (Figure 40) by explaining the need for a landscape architect and green roof consultant. The Detail subsection expands on reasons why the services of such a consultant are necessary for the project (explanation of problem context). It also describes the problem quantitatively, explaining budget allocations for landscaping and the need for a landscape architect's expertise to design the landscaping and estimate the costs of these designs.

1 Baseline	A Landscape Architect and a Green Roof Consultant is needed by the IPD Team to provide design concepts and scope for planting areas on the site and on accessible roofs of the building.
	Detail: a. The Validation Cost Estimate allocated $837k for landscape and irrigation work scope. b. The Validation Cost Estimate assumed only street level work and no roof level work, but allocated about $500k for enhancements. c. At Validation a Green Roof was not part of the baseline design or budget allocations. d. The Design Phase approved a courtyard scheme for Levels 5 and 6 to provide beds to meet operational needs as well as the 555 bed count. e. The Design Phase also approved a Pediatrics outdoor terrace at Level 7. f. The Core Group approved the pursuit of LEED® certification for the hospital, and green roofs provide a number of points to achieve that goal. g. A Landscape Architect is needed at this time to provide designs for pricing of site and roof-level landscaping.

Figure 41. Landscape Architect and Green Roof Consultant A3: Baseline

Figure 42 shows the Proposal section, which follows the same format as the Baseline section. It provides a problem description (Figure 40) and suggests hiring a landscape architect with expertise in green roof development. The A3 authors support this proposal with an explanation of the value this specialist's expertise would bring to the IPD team and the project. Specifically, this specialist can provide a landscaping plan to meet the city of San Francisco's requirements for trees lining the street, and provide detailed designs and cost estimates for green roofs.

2 Proposal	Hire the services of a Landscape Architect with expertise in green roof development. An informal evaluation of firms provided by IPDT members suggests that the firm C1 would provide the most value to the project, so the preferred option is to contract with them.
	Detail: a. A Landscape Architect is needed to develop the site in accordance with City requirements for street trees end coordinate with the building street level designs to meet the approvals of the City as well as the neighborhoods. b. A Landscape Architect with Green Roof experience is needed to provide the necessary technical expertise in the design, detailing/scope and pricing of green roofs. c. The budget and work scope for landscaping is limited, hiring a firm with combined experience with urban landscapes and green roofs is essential to get the highest value for the least fee.

Figure 42. Landscape Architect and Green Roof Consultant A3: Proposal

Figure 43 shows the Advantages section, which states the plan to evaluate multiple landscape architects as possible project consultants then lists why a green roof is important to the project. This serves as part of the problem analysis (Figure 40). Specifically, green roofs provide as many as 8 LEED® certification points (U.S. Green Building Council 2008), a pleasant visual for hospital patients and staff, and a mechanism for capturing and reusing storm water. The Advantages section also underscores the importance of a green roof to the project, reinforcing the need to hire a landscape architect with green roof expertise.

3 Advantages	The factors considered when selecting a landscape architect include local, OSHPD, high profile, and green roof project experience. The IPD team used these factors to summarize attributes and determine the advantages of landscape architect alternatives.
	Detail: An informal list of firms, based on prior experience, recognized experience, and reputation was formed to provide a base evaluation and test the need for a more formal interview/selection process. See CBA Table for Consultant Evaluation. a. For LEED® purposes, a Green Roof means is either cool (Energy Star), accessible or vegetated (the most common interpretation). In the case of our project, we mean all 3. A Green Roof will allow the project to achieve 6 to 8 LEED®-HC points. b. A Green Roof will provide visual relief for staff and patients from upper floors looking down onto the lower roofs as well as from the spaces adjacent to the Level 5 courtyard. c. A Green Roof extends the useful life of the roofing membrane below and reduces maintenance costs significantly by deferring replacement of roofing over a longer life. d. By increasing Storm-water retention a Green Roof can also reduce the flow rate and size and cost of roof drain piping. e. A Green Roof may improve the insulation properties of the roof assembly and will be verified by the Energy Model Consultant analysis.

Figure 43. Landscape Architect and Green Roof Consultant A3: Advantages

Table 24 shows the Consultant Evaluation CBA Table, which completes the problem analysis for this A3 (Figure 40). It compares five different landscape architect and green roof consultants, denoted C1, C2, C3, C4, and C5. Factors include experience with local (San Francisco Bay Area) projects, healthcare projects (specifically with OSHPD), green roofs, LEED®, high-profile projects, urban settings, CPMC, and IPD teams. The IPD team listed the consultants' attributes within each factor. They then selected the paramount advantage, "Much more close exper. [experience]," in the 'Local Project Experience' factor, and assigned it an importance of 100. They assigned other advantages' importances relative to the paramount advantage. After totaling the importances by alternative, the alternative with the highest total importance – and therefore the preferred one – ended up being C1. Figure 44 shows the A3 Analysis section and expands on the rationale for this choice.

Table 24. CBA Table for Consultant Evaluation

	C1		C2		C3		C4		C5	
Factor 1: Local Project Experience										
Must Criterion: Minimum of 2 local projects >$1 M in scope in last 10 years in the Bay Area.										
Want Criterion: More is better.										
Attribute:	San Francisco		San Francisco		San Francisco		Southern CA		Palo Alto	
Advantage:	**Much more close exper.**	100	**Much more close exper.**	100	**Much more close exper.**	100	!	0	**Close Experience**	85
Factor 2: Healthcare OSHPD Experience										
Must Criterion: Successful involvement with OSHPD projects.										
Want Criterion: More is better.										
Attribute:	Yes		Yes		Yes		Yes		No	
Advantage:	**More OSHPD Experience**	90	**More OSHPD Experience**	90	**More OSHPD Experience**	90	**More OSHPD Experience**	90	!	0
Factor 3: Green Roof Experience										
Must Criterion: Designed fuctional large green roofs in recent years.										
Attribute:	Yes		Yes		Yes		Yes		Yes	
Advantage:	!	0	!	0	!	0	!	0	!	0
Factor 4: LEED Project Experience										
Must Criterion: Minimum of 5 years experience with LEED.										
Attribute:	Yes		Yes		Yes		Yes		Yes	
Advantage:	!	0	!	0	!	0	!	0	!	0
Factor 5: High Profile Project Experience										
Want Criterion: Several high profile projects that occurred at a local level.										
Attribute:	Yes		No		No		No		No	
Advantage:	**More high profile local jobs**	60	!	0	!	0	!	0	!	0
Factor 6: Urban Setting Project Experience										
Must Criterion: Mimimum of 2 project experiences in an urban setting.										
Attribute:	Yes		Yes		Yes		Yes		Yes	
Advantage:	!	0	!	0	!	0	!	0	!	0
Factor 7: CPMC Project Experience										
Want Criterion: Successfully with CPMC in the past.										
Attribute:	No		Yes		No		No		No	
Advantage:	!	0	**More CPMC experience**	40	!	0	!	0	!	0
Factor 8: Integrated Team Delivery Experience (LEAN)										
Want Criterion: Integrated team delivery experience. If not, interest in participating.										
Attribute:	No		No		No		No		No	
Advantage:	!	0	!	0	!	0	!	0	!	0
TOTAL IMPORTANCE OF ADVANTAGES										
		250		**230**		**190**		**90**		**85**

4 Analysis	Of the Firms listed in this Informal evaluation, C1 appears to be able to provide the greatest value for the IPDT and the goals of capturing the green-roof LEED® points for the Project.
	Detail: a. Many local Landscape Architects exist but few have expertise in the design and detailing of Green Roofs, or have Healthcare experience. b. Portions of the Green Roof (such as the East/Van Ness side) could become Donor opportunities. c. A Landscape Architect with OSHPD experience is advantageous to the project over one without it. d. The EIR process will also need a Landscape Architect to develop design direction for all CPMC campuses. It is recognized that one of these firms may be considered for that work as well. Regardless, given the special nature of the Cathedral Hill Hospital project, it is felt that the factors used in this evaluation would be the most desirable for the IPD team.

Figure 44. Landscape Architect and Green Roof Consultant A3: Analysis

Figure 45 shows the Plan. It outlines the action plan (Figure 40): how a specific person from the IPD team will proceed in hiring a landscape architecture consultant, first attempting to negotiate a contract with C1 and, should that fail, interviewing the other consultants to determine their ability to integrate with the IPD team. If neither of these results in a hiring, the IPD team will try to find additional consultants to interview.

5 Plan	Steven Spaid will champion the implementation of the Action plan to hire a Landscape Architect. The options for taking action on this A3 are listed in the order of preference.
	Option 1: Select C1 and proceed with contracting a work scope and fee. Option 2: Proceed with interviews and discussions with each firm listed to further evaluate their abilities to meet the needs and goals of the Project. Option 3: Solicit additional firm names from sources at City, CPMC, and/or interested local action groups.

Figure 45. Landscape Architect and Green Roof Consultant A3: Plan

The Core Group considered the information shown in the A3. They discussed whether or not all information necessary to make a decision about hiring a landscape architecture consultant had been presented. When confident they had all they needed to make a decision, they discussed the suggested Plan to make sure it aligned with the project goals and budget. They then approved the Plan, by putting their initials at the bottom right corner of the A3 (Figure 40). The Approvals section serves a dual purpose. First, it shows that the Core Group has discussed the information presented in the A3 and deemed it acceptable. Second, it shows that they have agreed to the specific action plan. Thus, accountability is established for both the authors of the A3 and the Core Group. This A3 thus presented the plan part of the PDCA cycle, and the IPD team subsequently moved to the 'Do' portion of the PDCA cycle.

7.5 ANALYSIS OF THE SET-BASED DESIGN PROCESS AT THE CATHEDRAL HILL HOSPITAL PROJECT

When the IPD team first began work on the Cathedral Hill Hospital Project, they knew they had to use set-based design (the IFOA requires it). However, the team had not done set-based design before. In fact, most team members were learning it conceptually while trying to apply it (CHH IPD Team 2007, p. 358). Thus, when they started to use set-based design, they focused on developing sets of alternatives, not necessarily on how to evaluate them. It was hard for the team to keep considering alternatives, as they were used to delivering projects in a point-based design environment (Koga 2008b). John Koga encouraged the team to continue to develop and consider alternatives until the last responsible moment. This was not always desirable, but the team used the last responsible moment as "a crutch" (Koga 2008b) while learning when it would actually be appropriate to eliminate alternatives from consideration. A3s and CBA helped the team navigate the set-based design process, both in terms of generating alternatives and eliminating them.

Beyond generating alternatives, the team was initially unfamiliar with the best way to evaluate them. They first needed to develop alternatives with detail sufficient to show important differences between them. Preliminary development of alternatives was a learning exercise itself, as the team learned to appreciate and communicate the level of detail necessary to understand and evaluate alternatives (e.g., the wall penetrations example presented). Once the team was capable of understanding differences between alternatives, they could consider evaluating them. However, it was challenging to do so because different people evaluated alternatives based on different factors, criteria, and attributes. For instance, the IPD team simultaneously compared structural, architectural mechanical, and electrical systems (CHH IPD Team 2007). However, IPD team members did not establish a formal scale of importance, so they found it difficult to evaluate the advantages of the subsystems outside of their expertise. CBA makes the set-based design process easier to implement by providing a method for evaluating alternatives that supports group decision-making. A3s capture this evaluation and help the Core Group decide between alternatives as well.

Once the team became comfortable generating and considering alternatives, the A3 process and CBA were introduced to streamline and track these efforts. The Core Group implemented the A3 process to track and document decisions as required by the IFOA. The A3 acts as a "one page 'working' report summarizing the basis for incorporation of recommendations into the project. The summary includes information that initiated the effort, why it is relevant, the results of analysis, the ideas considered, and the outcome expected" (Koga 2008a). A3s also reported how the team involved in developing alternatives had evaluated them and the decision they made. The Core Group then used this information to make their own decisions.

When the A3 process was first implemented, each A3 was reviewed by the Core Group without its author present. However, as the process evolved, the author was invited to the Core Group meeting to "pitch" the A3. Early A3s did not include a CBA table. In fact, Cluster Groups (or sub-groups) developing sets of alternatives and describing them using A3s did not have a sound system to evaluate alternatives, so confusion arose about why a given alternative was selected by the team (Koga 2008b).

Once the team was comfortable with the A3 process, they began CBA training. CBA is a system for a team to evaluate alternatives based on the context of the decision (Suhr 1999, p. 151). CBA forces the team to anchor their decisions to relevant facts (Suhr 1999, p. 65). Thus, when sufficient detail exists to distinguish differences between alternatives, the team can begin to make evaluations. Moreover, CBA requires use of a single scale of importance, so the team can understand trade-offs of the importance of one advantage relative to another, and on that basis compare alternatives. At the time of this writing, CHH Cluster Groups are equipped with both A3s and CBA, therefore they are better able to develop and evaluate alternatives, i.e., implement set-based design, than they were at the project outset in 2005.

The set-based design process at CHH has evolved throughout the course of the design phase. Initially, the team focused their set-based design efforts on generating alternatives but struggled to keep all alternatives in consideration. However, as the team became more adept at developing sets, they were able to focus their attention on how to evaluate the sets. The introduction of A3s and CBA supports the team's efforts in developing and evaluating sets.

7.6 LESSONS LEARNED

The CHH IPD team pioneered set-based design efforts in an AEC project setting. Thinking in a set-based manner has changed the conversations between team participants. It has spurred innovation by encouraging consideration of out-of-the-box alternatives and evaluating tradeoffs between them, while keeping overall project value in mind. The team began to implement set-based design from the project outset on multiple building systems, developing different combinations of 500 alternatives (CHH IPD Team 2007) and evaluating them. As the team navigated the set-based design process, they developed a better process for implementing set-based design, including A3s and CBA.

Initially, it was difficult for the team to develop alternatives, and the sheer number of alternatives quickly became overwhelming. For future projects, it may be advisable to implement set-based design on a limited basis especially while the team is familiarizing itself with the process. Creating a Design Structure Matrix, for instance, could reveal where set-based design may be most helpful; that is, where it could reduce negative iteration. In the future, it would be helpful to implement these systems in support of set-based design efforts.

As executed on CHH, the owner's IFOA not only required collaboration, it also offered the owner's willingness to pay for innovation and thereby allows this collaboration to yield exceptional results. The owner's incentives for teamwork, e.g., including payment for additional analysis to develop the viscous damping wall system, led to selection of a system that better meets not only the structural performance but also the project goals than other options would have, i.e., it better optimizes the whole.

7.7 CASE-STUDY CONCLUSIONS

The CHH IPD team implemented set-based design from the project outset. However, the implementation thereof has evolved over the course of the design phase. When the structural system was selected, the team suggested alternative systems but struggled to develop them to the point where these alternatives could be evaluated, as they were accustomed to working in a point-based environment. Further, IPD team members had not necessarily had the opportunity to be involved in design decision-making before, and thus, they were unfamiliar with how to evaluate systems outside their own expertise. They required new tools and training to better implement set-based design.

Conversations between project team members are essential for successful project delivery. A3s can provide a basis for these conversations. Collaboration across disciplines and the triads of Lean Project Delivery System™ ™ (Figure 6) is necessary to generate A3s. Collaboration also helps determine an appropriate course of action given the information presented in A3s. Problem-solving A3s document the Plan step of the PDCA cycle, and guide conversations about how to Do (implement), Check, and subsequently Act to continuously improve processes or tasks needed for project delivery. A3s support the development of shared understanding of a process or task amongst team members. CBA further helps the team to develop a shared understanding and evaluate alternatives.

The Core Group of the CHH project is committed to the use of A3s and CBA. Their requirement that all submissions to them be in the form of A3s has supported collaboration amongst the IPD team members and has fostered consistency in communication and a learning environment on the project. The Core Group's commitment to CBA training and use has also fostered consistent communication and transparency in decision-making. Both A3s and CBA have improved the set-based design process on the project, enabling the team to generate and evaluate alternatives to support better project delivery.

CHAPTER 8. ACADEMIC EXAMPLE: SET-BASED DESIGN OF REBAR FOR A CONCRETE SHEAR WALL

The tool presented in this chapter, SetPlan, is based on collaborative efforts between Dr. John-Michael Wong and the author and was programmed by Dr. John-Michael Wong while he was a graduate student at UC Berkeley in the Structural Engineering, Mechanics, and Materials group of the Civil and Environmental Engineering department.

8.1 INTRODUCTION

To support lean project delivery, the project team must "collaborate, really collaborate" starting at the project outset. Collaboration promotes synergistic relationships and a shared understanding of the project. BIM models can further develop this shared understanding, by allowing the team to visualize the project in three dimensions. Our software development work consisted of tailoring a commercial BIM model to show multiple alternatives for an object or group of objects of the project, supporting a set-based design approach (e.g., Parrish et al. 2008a; Ward et al. 1995).

This chapter illustrates set-based design of a shear wall. It presents alternative wall shapes and reinforcement that reflect practitioner input about constructability. SetPlan, highlights differences between alternatives using information from the BIM model and from practitioner input. Specifically, it extracts information about bar size and count from the BIM model. Further, it highlights in the BIM model whether or not rebar can be bent with an automatic stirrup bender (vs. with a table bender). Automatic stirrup benders bend bars according to a programmed sequence, and therefore require less manual effort than traditional table benders, so fabricators prefer to bend bars with them. The tool compares alternatives, allowing team members to discuss value trade-offs between alternatives, with value propositions (Parrish et al. 2008b) or another means. Value propositions graphically relate, e.g., physical product characteristics, relative dollar, or time 'costs' to parameters that define value for different project stakeholders. They can then be used to assist project teams in developing shared understanding while gauging the advantages of different sets of alternatives, assigning a degree of importance to these advantages, and narrowing sets of design alternatives. Visualizing difference between alternatives provides information for making decisions about which alternative is preferred, e.g., using Choosing By Advantages (Suhr 1999). The shear wall example serves as a proof of concept for the set-based design tool and process.

8.2 BACKGROUND

This example illustrates the set-based design process for designing a shear wall. It shows what set-based design may *look* like for a shear wall on a real project. It explains tools and decision-making systems used for set-based design. Using design values from Nawy's (2000) *Reinforced Concrete: A Fundamental Approach*, the author generated a set of alternative shear walls that serve as a proof of concept. Workshop participants compared these alternatives visually using SetPlan and made design decisions using CBA.

This example presents the set-based design process for a shear wall 'decision unit.' The decision unit refers to the piece(s) of the structure or project of interest. Decision units will evolve throughout the project. When owners or project teams select the building materials, their decision unit may be the entire structure. As the project progresses, decision units will likely become smaller and more detailed. I selected shear walls for this example, rather than say, a beam-column joint, because they can be 'make or break' details on a project. Once the team selects a decision unit, they need to decide on the parameters of interest for that unit. For this example, parameters of interest include boundary element and wall dimensions, transverse rebar configuration, and transverse bar spacing. Parameters not considered include concrete strength, longitudinal rebar size and configuration, and others.

Shear walls resist lateral and gravity loads in a structure. Structural engineers commonly use shear walls in buildings located in regions of high seismic risk. These shear walls require special rebar detailing, especially in the boundary elements (ACI 2005). Seismic detailing requires a large amount of rebar in the boundary elements; this often creates congestion and thus placing difficulty. Placing concrete for boundary elements may also be difficult, as some boundary elements are wider than the shear wall (e.g., “dogbones”), requiring additional formwork. On the one hand, a wider boundary element offers more room for rebar, reducing the congestion issue. On the other hand, a wider boundary element requires additional formwork and possibly additional time for concrete placement.

8.3 USE OF VALUE PROPOSITIONS TO EVALUATE DESIGN ALTERNATIVES

Conceptually speaking, value propositions allow for each project stakeholder to understand the value tradeoffs within their own specialty and consider those of others. Value propositions illustrate trends in a given industry and can help project stakeholders understand each other’s perspective. Value propositions show data, enabling project stakeholders to determine importances of advantages for specific alternatives.

David Mar, a structural engineer in the San Francisco Bay Area, illustrated his thoughts at a workshop in December 2006 on the need to articulate and communicate value propositions associated with different designs. Figure 46 illustrates his concept of a value proposition in comparing two alternative designs of a shear wall. Alternative A is more efficient than Alternative B from his perspective, since there is ample wall length to develop shear force resistance necessary for structural performance. The longer wall length decreases the unit shear and reduces congestion, thus making rebar placement more straightforward. However, Alternative B is thought to be better for building occupancy because it provides more floor space and exposed perimeter (potential window and door penetrations, etc.). Alternative B is expected to be more expensive due to (1) additional rebar being needed for resisting overturning and shear forces over a shorter length than in Alternative A and (2) rebar congestion in Alternative B increasing labor costs. The questions are: How much more valuable is Alternative B than Alternative A? Is the additional cost 'worth it' given the benefits of B compared to A? A means of communicating relative values of these design alternatives, e.g., by defining a value proposition, is necessary to answer these questions. Value propositions of two or more project stakeholders can be considered at the same time, e.g., a formwork contractor's or a concrete placer's value proposition may be taken into account together with the structural engineer's when determining the importance of advantages, possibly making the balance tilt in favor of Alternative B as it has a smaller formwork contact area and a smaller concrete volume.

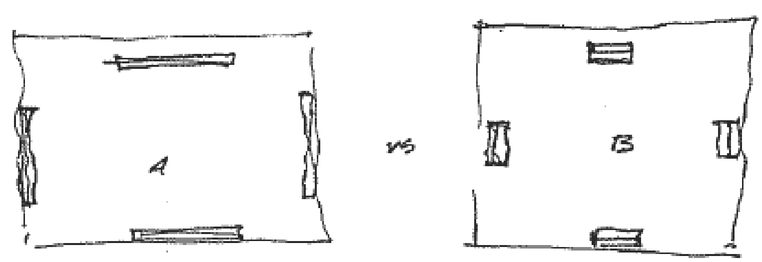


Figure 46. Comparison of shear wall designs for Alternative A vs. Alternative B (Mar 2007)

To express the relative value of Alternative B compared to Option A, the authors deconstructed the question into ‘chewable pieces.’ For example, one piece is: What is the difference in rebar cost between the two options? Figure 47 conceptually depicts the relative labor cost [relative $] (with 1 on the ordinate axis referring to rebar placed in a single layer) as it relates to different rebar configurations in a beam [ρ] (weight of rebar/volume of concrete). Figure 48 conceptually depicts the relative labor cost [relative $] as it relates to different rebar configurations in a wall [ρ]. In the figure, a single layer of reinforcement is assigned a value of 1.3 in relative cost (the y-intercept of the graph). This reflects the assumption that the easiest wall placement is 1.3 times more expensive than the easiest beam placement, and that was assigned a relative cost of 1 (Figure 47). The points of overlap (e.g., where single layer and double layer meet) represent the “critical densities” for a given design option. For instance, consider design Alternatives A and B, denoted by ‘des. A’ and ‘des. B’ on the graph, respectively. The ‘des. A’ density is greater than the critical density between the single layer and double layer lines. So, for Alternative A (‘des A’), it would be more cost effective to use double layer rebar rather than a single layer of rebar. In fact, a single layer may no longer be feasible.

Value propositions are data rich and thus ease communication between project stakeholders. The graphs eliminate some of the jargon issues experienced in conversations between stakeholders. For instance, structural engineers often talk about rebar in terms of a reinforcement ratio, ρ, and ACI 318 sets an acceptable range of values for it (a ‘must’ criterion). However, rebar placers do not talk about reinforcement ratios; it is not a parameter they have a say over or control. The fabricator-placers on the research team talk about a design in terms of Structural Activity Codes (SACs) (details on these are given later in this chapter). At an early Rebar Workshop, they were surprised to learn about the significance of ρ and, likewise, structural engineers on our team were surprised to learn about the significance of SACs. Neither party outright understood the jargon of the other party. A graph that compares relative cost with rebar densities alleviates confusion due to jargon, as it expresses an interrelationship between the work done by these stakeholders. Furthermore, value propositions can be qualitative or show actual data and quantitative relationships, thus reducing the reliance on ‘hunches’ and ‘rules of thumb.’

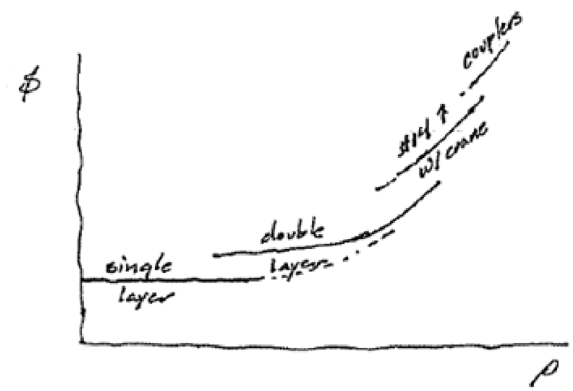


Figure 47. Rebar value proposition concept for beams (Mar 2007)

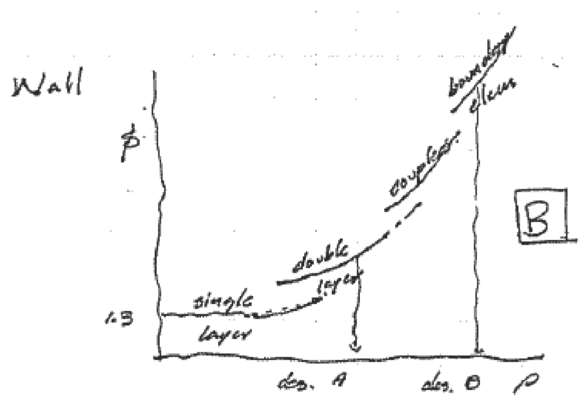


Figure 48. Rebar value proposition concept for walls (Mar 2007)

In a traditional hard bid scenario, project stakeholders are hired sequentially to work on a project. Owners, architects, and structural engineers set the requirements of a structure during the programming and Schematic Design phases (Figure 3). The structural engineer designs the structure by preferred means to meet the constraints known during Schematic Design and Design Development (Figure 3) (i.e., outlined geometry, design loads, project budget, and structural functionality), and optimizes it to meet one or several criteria such as least weight, least cost (based on quantity takeoffs), or least floor-to-floor height. Designers carry their decisions forward through Design Development and Construction Documents (Figure 3), and then release design documents for construction. Construction documents are put out for bid, general contractors (GCs) prepare bids for the work based on quotes from many subcontractors, bids are reviewed, and then a GC gets selected. The GC in turn hires subcontractors. By the time the rebar fabricator and placer are hired, it is difficult for them to have a direct conversation and much if any input at all in the design. The design is considered complete, even though rebar placing drawings remain to be developed and approved for conformance with design intent. Input from project stakeholders, especially those brought on board late, then often leads to negative iteration in design and causes rework (Ballard 2000c). This practice makes it hard if not impossible for project participants to develop shared understanding of the project's needs and collaborate to jointly think of opportunities to meet them.

In contrast, in an integrated project team environment, the Integrated Form of Agreement (IFOA) requires project stakeholders collaborate throughout the design process (Farrow 2007; Lichtig 2006; Matthews and Howell 2005). They can thus bring value propositions (information they may not disclose otherwise) to the table when meeting to discuss alternative designs with others and thereby enrich everyone's understanding thereof. For example, a rebar placer may use a value proposition to help the structural engineer understand whether it is more economical to use a single layer of rebar or a double layer in a given beam provided both are structurally feasible. Should a mechanical subcontractor later ask to cut through a beam with a pipe or duct, the team can use the value proposition as support for re-considering the initial decision. A CBA analysis can help to determine whether the better decision is to ask the mechanical subcontractor to re-route the pipe or duct vs. redesign the beam with different reinforcement.

8.4 STRUCTURAL ACTIVITY CODES

The rebar fabricator-placers on our research team use Structural Activity Codes (SACs) as a method of organizing pieces by structural element type, to categorize quantity take-offs while developing estimates aided by specialized software, and for accounting purposes (an open research question is: To which degree are SACs universally applicable and useful?). Table 25 shows a partial list of SACs. Labor rates are associated with each of the different SACs for various bar sizes, usually expressed in units of pounds of rebar placed per worker day (lb/worker-day). A fabricator may use the same SAC for multiple labor rates, depending on congestion (Soulé 2006b).

Structural engineers and design cost consultants estimate preliminary costs for rebar but do not take SACs into account; rather, these estimates are typically based on aggregated steel weight alone, using, e.g., values from *RS Means Building Construction Cost Data* (R. S. Means 2008). However, cost estimates included in RS Means do not break down cost the same way as SAC codes. For instance, RS Means includes a cost estimate for ‘Grade Walls, 8” thick, 8’ high,’ but SAC codes break the data down further, into specific types of walls. Sandy Soulé, President of Soulé Software (software that integrates rebar accounting, estimating, and fabrication), explains, “In general, their numbers might be ok for calculating rough project costs, but not accurate enough for bidding” (Soulé 2009). Value propositions add nuance and help to mitigate these discrepancies by illustrating the different relative costs of rebar placement within a given SAC. Rebar fabricators or placers could develop a value proposition for each SAC, e.g., comparing the labor rate with bar size for a given SAC. To compare different SACs, multiple value propositions need to be compared.

8.5 REBAR BENDING SPECIFICATIONS

The Concrete Reinforcing Steel Institute (CRSI) classifies bars as either straight or bent. Bent bars are classified as light bending, heavy bending, or special bending with the following definitions (CRSI 2009):

a. LIGHT BENDING. All #3 bars, all stirrups and ties, and all bars #4 through #18, which are bent at more than six points in one plane, or bars which are bent in more than one plane (unless classified as "Special Bending"); all one plane radius bending with more than one radius in any bar (three maximum); or a combination of radius and other type bending in one plane – where radius bending is defined as all bends having a radius of 12 inches or more to outside of bar.
b. HEAVY BENDING. Bar sizes #4 through #18, which are bent at not more than six points in one plane (unless classified as "Light Bending" or "Special Bending") and single radius bending.
c. SPECIAL BENDING. All bending to special tolerances (tolerances closer than those listed in Figures 7-3 and 7-4 in Chapter 7 of this *[2009 CRSI] Manual [of Standard Practice]*), all radius bending in more than one plane, all multiple plane bending containing one or more radius bends, and all bending for precast units.

Table 25. Structural Activity Codes (SACs) (Bennion 2007)

SAC	Description
1	Caissons
2	Pile Caps
3	Foundation Mat
4	Mat (Spread) Footings
5	Spread Footings
6	Continuous Footing
7	Grade Beams
8	Tie Beams
9	Slab On Grade
10	Columns
11	Columns, Pedestals
12	Walls
13	Walls, Shearwalls
14	Walls, Retaining Walls
15	Walls, Shotcrete
16	Mild Beams
17	Link Beams
18	Mild Slabs, One & Two-Way
19	Slabs On Metal Deck
20	Mild Slabs, Post-Tension

Table 26. Bar numbers, diameters, and areas (CRSI 2006)

Bar No.	Diameter, (in)	Cross-Sectional Area, (in^2)
#3	0.375	0.11
#4	0.500	0.20
#5	0.625	0.31
#6	0.750	0.44
#7	0.875	0.60
#8	1.000	0.79
#9	1.128	1.00
#10	1.270	1.27
#11	1.410	1.56
#14	1.693	2.25
#18	2.257	4.00

8.6 DESIGN OF SETPLAN, A SET-BASED DESIGN TOOL

Practitioners involved in this research shared their perspectives on value propositions used to make design decisions (Parrish et al. 2008b). SetPlan, presented herein, supplements the spatial and material information contained in a BIM model with value proposition information (Parrish et al. 2008b). It works side-by-side with an existing BIM tool, Tekla Structures 14.0, so information such as rebar counts can be extracted from the Tekla Structures 14.0 model. Moreover, information about whether or not a bar can be bent with an automated stirrup bender (e.g., the Idea Machine rather than a table bender) and is added to the Tekla Structures 14.0 model. SetPlan displays information about rebar fabrication during design that is typically not available until the construction team is selected. The current implementation of SetPlan presents information that is general and does not reflect specifics from any one fabricator. For SetPlan to be most useful for a given project, it should include specific information about the capabilities of the fabricator and placer who actually are hired on that project and use this information during the design phase to influence design decisions. Figure 49 shows the role of the tool in the design process. The tool makes information from the rebar fabricator, placer, and structural engineer explicit and visual, creating a shared understanding and avoiding some jargon issues between team members.

8.6.1 IMPLEMENTATION DETAILS

John-Michael Wong used Microsoft .NET C# 2008 to program SetPlan. This programming language was selected for compatibility with the Tekla Structures 14.0 Open API (see http://www.tekla.com/uk/solutions/Pages/basic-concepts.aspx). SetPlan is integrated loosely with Tekla Structures 14.0, i.e., the data it uses is independent of modeling software, provided the model supports reading and writing the required information. The Tekla Structures 14.0 .NET Open API makes this information readily accessible, and is thus used for this example. SetPlan reads data from the Tekla Structures

14.0 model by iterating through all the objects in it of a particular type or through all the objects that the user selected. SetPlan provides a graphical user interface in a single window that can display different types of information.

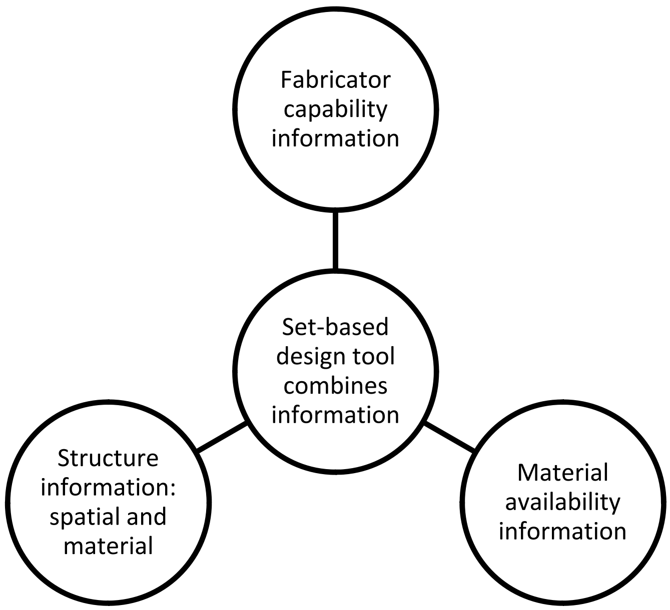


Figure 49. Role of the set-based design tool in the design process

8.6.2 Information Required from the Tekla Structures 14.0 Model

SetPlan gathers information to compare alternatives. It counts the number of short direction ties, long direction ties, hoops, and longitudinal bars in the boundary elements and curtain of a shear wall. (Rebar in the wall itself is referred to as ‘curtain’ rebar). It also counts the number of vertical and horizontal bars in the shear wall. However, Tekla Structures 14.0 creates rebar objects without this data. When a user draws rebar in the Tekla Structures 14.0 model, (s)he does not specify the rebar’s function (i.e., long direction tie, short direction tie, etc.). Thus, users must input this metadata into Tekla Structures 14.0 in the “Name” field of an object’s properties. Table 27 lists the object names SetPlan searches for, their corresponding physical meaning, and their designation in the Tekla Open API (API Object Class).

Table 27. Names for different rebar and concrete objects in the model

Object Name	Description	API Object Class
BE1, BE2	Concrete volume for boundary elements	Beam
SHEARWALL	Concrete for wall	Beam
BE1_H, BE2_H	Boundary element hoops	SingleRebar
BE1_VS, BE2_VS	Boundary element vertical rebar	RebarGroup
BE1_SDT, BE2_SDT	Boundary element short direction transverse ties	SingleRebar
BE1_LDT, BE2_LDT	Boundary element long direction transverse ties	SingleRebar
CH	Wall horizontal rebar	SingleRebar
CV	Wall vertical rebar	SingleRebar

Structural engineers require some information during design not necessary for rebar fabrication or placement (e.g., required total area of rebar in an element). The structural engineers may not make this information explicit in the model (Wong 2008). Such information must be added to the Tekla Structures 14.0 model so it can work with SetPlan and provide most value to the project team. For example, the process for designing a reinforced concrete shear walls involves parameters such as ρ, the reinforcement ratio that compares the cross-sectional area of steel with that of concrete. This parameter is not necessary for construction, nor used by rebar fabricators, but it is essential for completing a structural engineering analysis and design. For the model to be most useful in the early stages of set-based design, it needs to contain this type of design parameter. Design parameters help define the 'must' criteria, attributes, and alternatives for shear wall design (Parrish and Tommelein 2009).

Conversely, fabrication requires some information not necessary for design. For instance, fabricators use standard bending shapes to create hooks and stirrups, but structural drawings typically just specify “stirrups” at a given spacing. Information about standard bending shapes, according to the ACI Detailing Manual, ACI 315 (ACI 2004), also aids in design decision-making, and is thus useful in the model. Tekla Structures 14.0 contains internal bending shapes (defined by the object’s SHAPE_INTERNAL data) that map to ACI 315 bending shape designations using the SHAPE variable. SetPlan also requires information from outside the model.

8.6.3 INFORMATION REQUIRED FROM OUTSIDE THE TEKLA STRUCTURES 14.0 MODEL

Figure 50 shows the set-based design tool’s main window, which displays information about the shear wall (Figure 51). At the top, it shows an integrated web browser window that allows a space for custom tools and freeform information presentation. The ‘Bar Size Dashboard’ provides information about material availability, bending tolerance, cost, and placing time for *one* bar. Rebar fabricators in the San Francisco Bay Area provided dashboard values, reflecting trends, not actual data. In the lower left corner, it shows dimensions of each objects, as well as the quantity of bars of a given type (e.g., hoops, short direction ties, etc) in the boundary elements and the wall. The lower left corner of Figure 50 also shows bar sizes and concrete strengths for the boundary elements and the wall. The lower right corner shows the data SetPlan is grabbing.

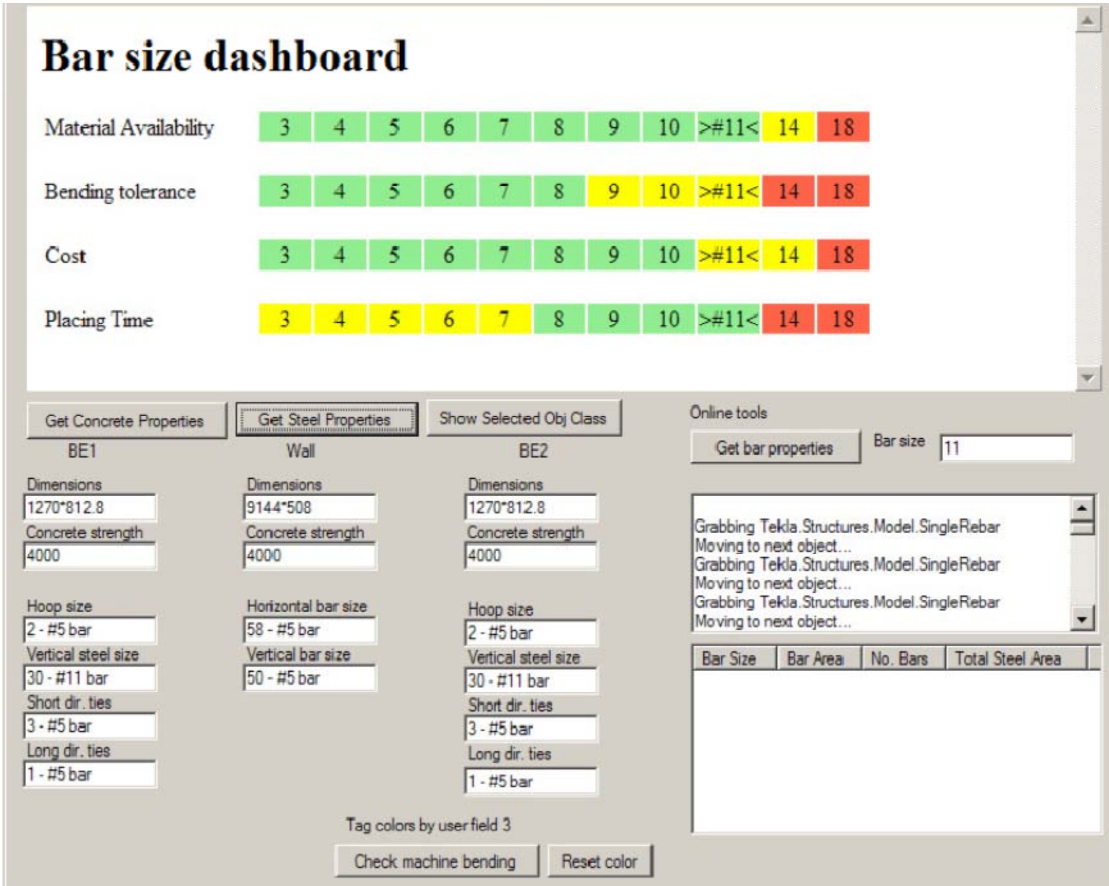


Figure 50. Main window of SetPlan (best viewed in color)

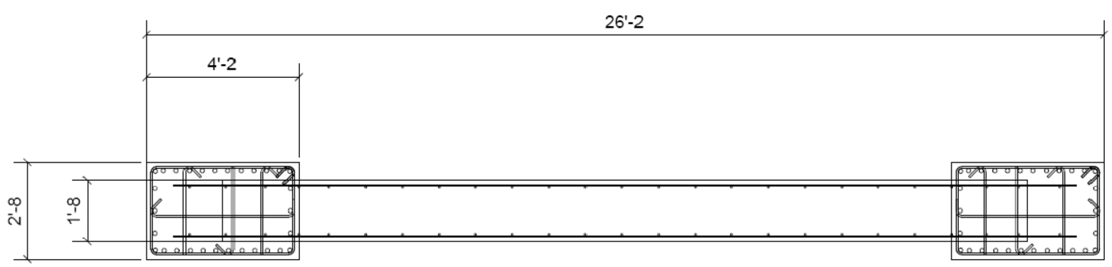


Figure 51. Plan view of the design shear wall (redrawn from Nawy 2000)

Delineations between colors in the dashboard are arbitrary, and depend on the project team's capabilities and preferences. 'Material Availability' assesses how long it will take to receive material for the project. Green denotes material being readily available at a fabrication shop, which is the case for bar sizes #3 through #11. Mills run #14 bar less frequently than the other sizes, and #18 even less frequently (Richenberger 2008), so the dashboard shows these sizes with yellow and red, respectively. ‘Bending Tolerance’ assesses how many times a bar needs to be bent to conform with tolerances mandated in the CRSI Manual of Standard practice (CRSI 2009). Green on the dashboard denotes bars meet requirements after going through the automatic stirrup bender once or twice. Yellow denotes a bar requires three bends to meet standards, and red denotes a bar requires more than three bends. Rineman (2008) explained automatic stirrup benders (e.g., the “Idea Machine,” http://harrisalinasrebarshop.blogspot.com/2009/02/idea-machine.html) could bend up to a #8 bar; however, some fabricators may not have this machine. Thus, the coloring for this factor may look different for another project team. ‘Cost’ assesses the productivity rates for placing a given bar size. This dashboard assumes productivity begins to decline when placing bars #11 and larger because placing these requires cranes instead of hand placement, so productivity decreases. Coloring of the ‘Cost’ row follows this trend; green denotes most efficient placement, yellow is less efficient, and red is least efficient. ‘Placing time’ assesses productivity of placement in terms of bars placed per hour. Green denotes the highest bars/hour rate, yellow denotes a lower rate, and red denotes the lowest rate. In a real project setting, the project team would adjust the coloring on the dashboard to reflect their capability data.

Figure 50 also includes a ‘Check Machine Bending’ button at the bottom of the SetPlan main window that color codes the BIM model according to whether or not a bar can be bent with an automatic stirrup bender.

8.6.4 Using the Tekla Structures 14.0 Model for Additional Visualization

Dr. Wong and I programmed SetPlan to assess whether or not a given piece of rebar can be bent with an automatic stirrup bender. Some automatic stirrup benders can do heavy bending (less than six points of bending in one plane) up to and including #8 bars; however, most automatic stirrup benders cannot bend bars larger than #6, so SetPlan uses #6 as an upper limit for bending with an automatic stirrup bender. Automatic stirrup benders can easily bend bars into shapes listed in the 'Standard Shapes – Heavy Bent' table of the *CRSI Manual of Standard Practice* (2009, p. 7-5), provided the total spacing between bends does not exceed 3 ft. This information complements the spatial information and the model displays both, making it more useful for design.

SetPlan illustrates whether or not a bar can be bent with an automatic stirrup bender by color coding rebar in the Tekla Structures 14.0 model. The tool first extracts rebar information for each rebar object, then checks the rebar data with the automatic stirrup bender capabilities. This bending information is then written back into the model using user-defined attribute (UDA) fields. The tool sets the UDA to yellow for straight bar objects, green for bar objects that can be bent with the automatic stirrup bender, and red for objects that cannot. Once this information is written to the model database, users can opt to visualize colors of the objects based on the UDA value. Coloring objects to display value proposition information can be extended to show other forms of information. Color coding objects makes visualizing differences in alternatives straightforward, and colors can be manipulated from within Tekla Structures 14.0's model space. Colors display information in a common platform and can illustrate the implications of design decisions.

8.7 PROOF OF CONCEPT: SHEAR WALL EXAMPLE

The example of reinforcing a concrete shear wall illustrates the use of a value proposition and the set-based design tool. This example follows the design process from the conceptual design phase (a shear wall is selected as the structural system) through the selection of a rebar configuration in the Design Development phase. In a real project setting, several stakeholders each would bring a suite of value propositions to a meeting; however, for this example, the author considers only the interactions between the structural engineer (SE) and the rebar placer (placer). Value propositions can inform the rebar design process by presenting means to more objectively assess fabrication and construction concerns. The value propositions do not serve as substitutes for design conversations, but they can help to inform the decision-making process.

The shear wall alternatives are designed according to ACI 318 (ACI 2005) for a 12 story structure that is 148 ft. high with equal 22 ft. bays. Loads on the shear wall are (1) A factored gravity load of W_u = 4,800,000 lbf, (2) A factored moment at the base of the wall due to seismic loads (from lateral analysis) of $M_u = 554 \times 10^6$ in.-lbf, (3) The maximum axial force on the boundary element, P_u = 4,500,000 lbf, and (4) The horizontal shear force at the base, V_u = 885,000 lbf (Nawy 2000).

The SE and the placer are assumed to work in an integrated project team. This allows them to communicate directly about design alternatives and preferences (as opposed to having to use requests for information (RFIs) or the like, and pass these along via the general contractor, the owner's agent, and the architect prior to reaching the SE). Figure 51 shows a plan view of the shear wall as shown in Nawy (2000). The SE designs a shear wall to meet the demands as were listed.

The value proposition used in this example was developed based on data collected from Howard Bennion of Pacific Coast Steel, Inc., a San Francisco Bay Area rebar fabricator-placer. Since the data itself is proprietary, rates in Figure 52 are fictitious yet crafted to reflect trends that are found in the original data, and these trends were validated using data from other fabricator-placers in the San Francisco Bay Area. The placer's value proposition for rebar placement in shear walls is expressed in terms of relative labor productivity rates (rather than in terms of relative cost). Increasing the bar size increases the productivity rate for #3 to #14 bars. For bar sizes #3 to #11, a crew can place the bars by hand, so the productivity rate increases because each bar is heavier than the last, but not so much heavier that the placing method changes. Thus, crews can move more weight in the same amount of time. This is one reason why placers in this region seldom use #3 rebar in commercial building construction. A #14 bar requires crane placement, so crews may place fewer bars per hour than when they can move bars by hand (due to time spent waiting for the crane), however, the increase in pounds placed (#14 bar weighs 7.65 lb/ft) outweighs the decrease in pieces placed, so the labor productivity rate is higher for a #14 bar than a #11 bar for shear wall placement. However, productivity rates decrease when upsizing from #14 to #18 due to the weight and diameter of the #18 bar. Figure 52 illustrates that placing straight bar is more productive than placing light or heavy bent bar.

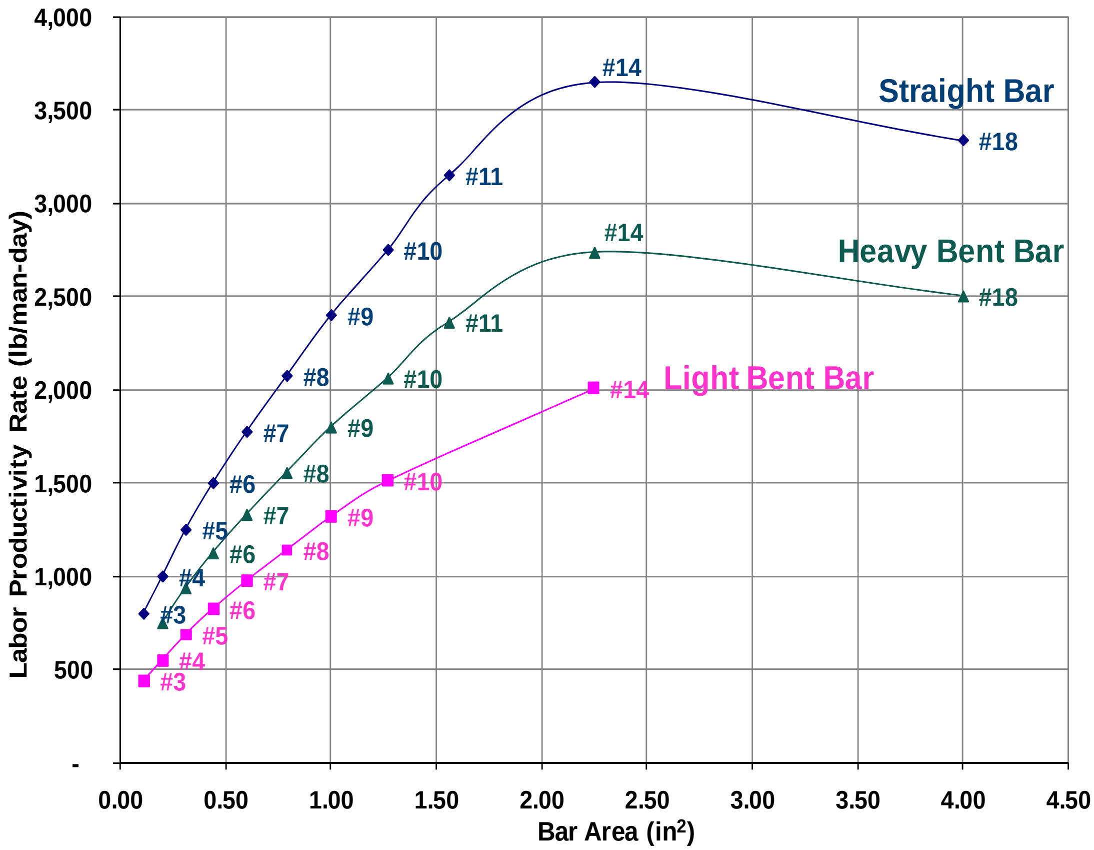


Figure 52. Rebar Placer's value proposition for longitudinal rebar in shear walls

8.7.1 Developing a Set of Shear Wall Alternatives

The author developed a set of shear wall alternatives with different transverse rebar sizes, spacings, and wall shapes. After comparing transverse rebar spaced at 4 in. and 6 in., the author decided to pursue alternatives with 6 in. spacing, as this spacing is permissible by ACI 318 (ACI 2005) and leaves most room for concrete and additional rebar (if necessary). The author chose to pursue alternatives with #5 bar used for transverse reinforcement. She eliminated #3 bars from consideration because practitioners involved in this research suggested #3 bar is often too flexible, making placing difficult. Bars larger than #6 cannot be bent with most automatic stirrup benders, and thus require special equipment. Therefore, only alternatives with #4, #5, or #6 transverse bars and 6 in.

transverse spacing were considered. In total, 9 walls were considered in this analysis. Figure 53 shows a sampling of this shear wall design set.

The SE can use the placer's value proposition as a design aid. SEs often try to minimize the total weight of rebar in a project. When rebar is priced by weight, minimizing the total weight in a project presumably will reduce material costs. However, the savings in material cost may be outweighed by the extra labor costs associated with having to place a larger quantity of lighter bars. The value proposition reflecting the rebar placer's productivity (Figure 52) can be used in this example to gauge the difference in labor productivity rates for different longitudinal bar sizes, relative to the cost of rebar. Decision-making based on facts reflected in the value proposition is more rational than decision-making informed by 'rules of thumb' that each party is accustomed to using.

Based on the placer's value proposition (Figure 52), it would seem that the choice is to use enough #14 bars in the longitudinal direction to achieve the required A_s, 32 in^2, which turns out to be 14 bars in this case. However, this is not an acceptable alternative as the diameter of the #14 bars violate ACI 318's rebar spacing requirements. Thus, the decision-makers eliminate alternatives reinforced with #14 bar from the shear wall design set. However, shear wall alternatives reinforced with #11 bars in the longitudinal direction remain in the shear wall design set. The shear wall boundary elements for all alternatives are thus reinforced with #11 bars in the longitudinal direction (total number of #11 bars varies from 26 in Shear Wall C to 30 in Shear Wall A). #5 bars @12 in. on center are used in both directions for reinforcement curtains in all of the walls.

Figure 53 shows three shear wall design alternatives that vary in terms of wall shape, boundary element shape and size, and transverse rebar configuration, but that all have the same length. However, each of these alternatives is reinforced with #5 bars in the transverse direction. Shear wall A is a "dogbone," with wider boundary elements than the wall. The wall is 20 in. wide, and the boundary elements are 32 in. wide and 50 in. long. The boundary elements of shear walls B and C are as wide as the walls themselves. Shear wall B is 26 in. wide. Its boundary elements are 26 in. wide and 50 in. long. Shear wall C is 20 in. wide, and its boundary elements are 20 in. wide and 80 in. long. Note the number of pieces of rebar in each shear wall. The boundary elements in shear wall C have many rebar ties to achieve the required rebar area.

Figure 54 shows these same shear wall alternatives, but with the rebar named as objects for use with SetPlan.

8.7.2 Visualizing Differences Between Shear Wall Alternatives using SetPlan

Visualizing the shear wall design alternatives allows the project team to find differences between the alternatives that may not otherwise be so obvious. For instance, the difference in boundary element length may not be obvious in narrative form, but is clear in the drawing (Figure 54). To further aid in understanding differences between alternatives, users may elect to use the set-based tool to color code the set of shear wall alternatives, ash illustrated in Figure 55. Green color indicates a piece of rebar can be bent with an automatic stirrup bender. Fabricators could use an automatic stirrup bender to bend the boundary element hoops for each shear wall alternative. Long direction ties can also be bent for every shear wall. The short direction ties cannot be bent with an automatic stirrup bender for any shear wall. The yellow color of all curtain steel indicates it is straight bar.

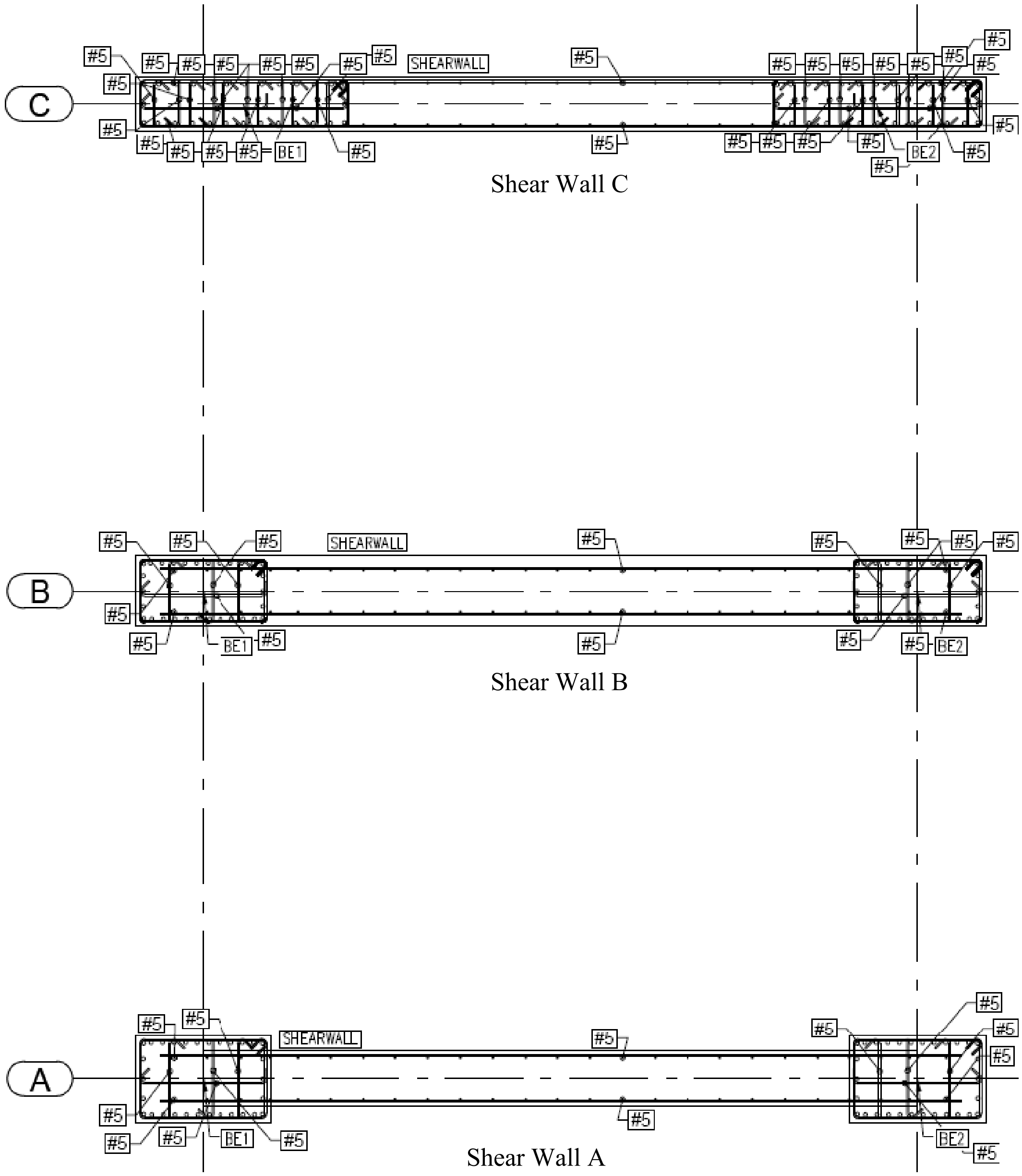


Figure 53. Set of shear wall alternatives

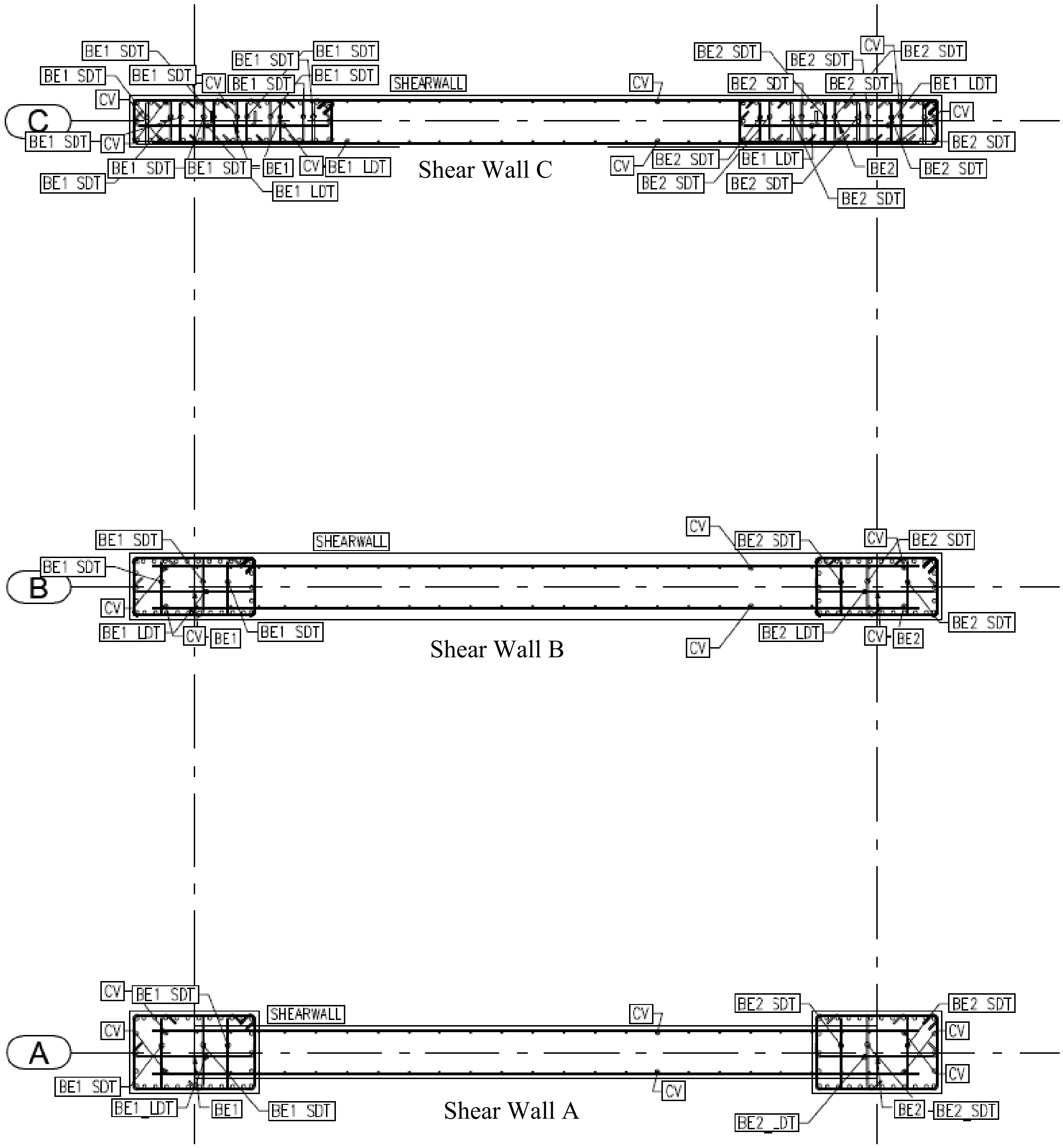


Figure 54. Set of shear wall alternatives, with rebar named as objects for SetPlan

In color, differences between alternatives become clear. Project team members can *see* the impact of a given design decision in terms of ability to table bend bars. Practitioners involved in this research commented SetPlan could be very useful in practice, as it brings issues to the fore for the project team to discuss. For instance, a structural engineer on our research team commented he was surprised to see the short direction ties could not be table bent. A rebar fabricator explained that bars like the short direction ties, with hooks on only one end, cannot necessarily be bent with all automatic stirrup benders, because this shape does not appear on p. 7-5 of the *CRSI Manual of Standard Practice* (CRSI 2009). Conversations like this could lead to development of a new alternative (e.g., add 90° hooks to the ends of the short direction ties) or suggest further exploration of alternatives by the team to gain deeper understanding of value tradeoffs.

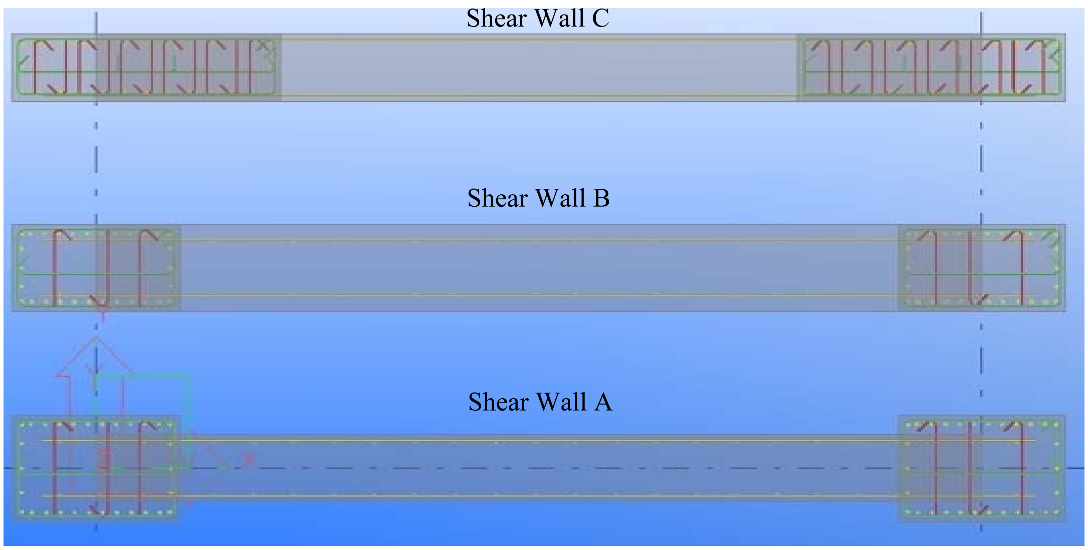


Figure 55. Color codes shown inside the modeling software (best viewed in color)

8.7.3 SELECTING A SHEAR WALL ALTERNATIVE USING CBA

At a workshop on February 13, 2009, the author presented three alternative shear walls, from the nine she considered, to workshop participants. She had selected these three shear walls reinforced in the transverse direction with #5 bars because #5 bars provided ample space for longitudinal bars (using #6 bar for transverse reinforcement led to congestion of longitudinal bar in Shear Wall C) and used fewer pieces than if #4 bars were used.

She then instructed the workshop participants in using CBA to select a shear wall from the set of alternatives. She gave them a CBA table that listed a preliminary list of factors and criteria, and had the group discuss the factors and criteria and add others, until those listed were sufficient to select a shear wall. Workshop attendees included a detailer (former ironworker foreman), structural engineers, a software developer, and a CRSI representative, among others. Table 28 shows the CBA table they developed.

8.7.3.1 Factors and Criteria Considered in the CBA Analysis of the Shear Wall Alternatives

Factors and criteria for this exercise were agreed upon by the workshop participants. Rather than have criteria that reflect one stakeholder's views, as was the case in Chapter 5, the criteria in this example reflect a consensus of the participants.

The factor **Thickness of boundary element** refers to the thickness of the boundary elements for each wall. Boundary elements are by design assumed to act as columns, and as such, often have more rebar congestion than the rest of a shear wall. The 'must' criterion states the boundary element must be at least as thick as the wall. This ensures curtain steel can be continuous into the boundary element, rather than being bent to fit into it. The 'want' criterion expresses preference for a thinner wall, as thinner walls leave more floor space.

The factor **Number of corners to form** refers to the number of corners in each shear wall. Forming corners can be difficult because, especially when the space between corners is small. There is no 'must' criterion for this factor. The 'want' criterion expresses the preference for fewer corners, as this simplifies formwork geometry.

Table 28 (part 1 of 2). CBA table comparing shear wall alternatives

FACTORS	ALTERNATIVES					
	WALL A		WALL B		WALL C	
1. Thickness of boundary element Must Criterion: Boundary element must be at least as thick as the wall Want Criterion: The thinner wall is preferred						
Attributes:	32 in.		26 in.		20 in.	
Advantages:		0	6 in. thinner	80	12 in. thinner	100
2. Number of corners to form Must Criterion: No must criterion for this factor Want Criterion: All else being equal, fewer corners are preferred						
Attributes:	12 corners		4 corners		4 corners	
Advantages:		0	8 fewer corners	95	8 fewer corners	95
3. Length of transverse rebar Must Criterion: Length of transverse steel must provide enough area to meet ACI 318 (2005*) ACI 318 (2005*) Equation 21-3: $A_{sh} = 0.3(sb_c f_c'/f_{yt})[(A_g/A_{ch}) - 1]$ ACI 318 (2005*) Equation 21-4: $A_{sh} = 0.09sb_c f_c'/f_{yt}$ Want Criterion: Shorter length is preferred						
Attributes:	312 in.		280 in.		500 in.	
Advantages:	188 fewer in.	70	220 fewer in.	78		0
4. Number of table bends Must Criterion: No must criterion for this factor Want Criterion: Fewer table bends are preferred						
Attributes:	6 table bends		6 table bends		22 table bends	
Advantages:	16 fewer table bends	45	16 fewer table bends	45		
5. Transverse spacing of bars Must Criterion: Transverse spacing must meet ACI 318 (2005*) 21.4.4.2 a-c ACI 318 (2005*) 21.4.4.2: Transverse spacing shall not exceed the smallest of (a), (b), or (c) ACI 318 (2005*) 21.4.4.2 (a): one-quarter of the minimum member dimension ACI 318 (2005*) 21.4.4.2 (b): six times the diameter of the longitudinal reinforcement ACI 318 (2005*) 21.4.4.2 (c): s_o, as defined by Eq. (21-5) ACI 318 (2005*) Equation 21-5: $s_o = 4+((14-h_x)/3)$; h_x = horizontal spacing of hooks <=14 in. Want Criterion: All else being equal, greater spacing is preferred						
Attributes:	4 in.		4 in.		4 in.	
Advantages:	No avantage of any alternative					
6. Room for MEP features Must Criterion: Boundary element must be at least as thick as the wall Want Criterion: Prefer a thinner wall to "hide" MEP features						
Attributes:	12 in.		0 in.		0 in.	
Advantages:	12 in. more	82		0		0
7. Length of boundary element Must Criterion: Boundary element must be long enough to hold concentrated longitudinal reinforcement Want Criterion: Prefer a longer boundary element to minimize wall steel to place						
Attributes:	50 in.		50 in.		80 in.	
Advantages:		0		0	30 in. more	25

Table 28 (part 2 of 2). CBA Table comparing shear wall alternatives

FACTORS	ALTERNATIVES					
	WALL A		WALL B		WALL C	
8. Number of hooks Must Criterion: Hooks must provide enough area to meet ACI 318 (2005*) ACI 318 (2005*) Equation 21-3: $A_{sh} = 0.3(sb_c f_c'/f_{yt})[(A_g /A_{ch}) -1]$ ACI 318 (2005*) Equation 21-4: $A_{sh} = 0.09sb_c f_c'/f_{yt}$ Must Criterion: Space between hooks must meet ACI 318 (2005*) ACI 318 (2005*) 21.4.4.3: Horizontal spacing... of overlapping hooks, h_x, shall not exceed 14 in. Want Criterion: Fewer hooks are better						
Attributes:	10 hooks		10 hooks		28 hooks	
Advantages:	18 fewer hooks	40	18 fewer hooks	40		0
9. Total area of transverse steel, A_{sh}/ft Must Criterion: Total area of transverse steel must meet ACI 318 (2005*) Eqn 21-3 and 21-4 ACI 318 (2005*) Equation 21-3: $A_{sh} = 0.3(sb_c f_c'/f_{yt})[(A_g /A_{ch}) -1]$ ACI 318 (2005*) Equation 21-4: $A_{sh} = 0.09sb_c f_c'/f_{yt}$ Want Criterion: Smaller area is better						
Attributes:	715 in^2/ft		640 in^2/ft		1130 in^2/ft	
Advantages:	415 in^2/ft less	22	490 in^2/ft less	25		0
10. Erection stability Must Criterion: Must be stable according to established safety criteria for the job (height usually dictates) Want Criterion: More stable, the better						
Attributes:	stable		stable		stable	
Advantages:	No avantage of any alternative					
11. Steel grade Must Criterion: Grade must be at least 60 ksi Want Criterion: Use the same steel grade throughout wall Want Criterion: Higher steel grade may be preferred to relax spacing requirement						
Attributes:	60 ksi		60 ksi		60 ksi	
Advantages:	No avantage of any alternative					
TOTAL IMPORTANCE:		237		338		220

* or applicable version of ACI 318

The factor **Length of transverse rebar** refers to how much rebar is needed in the transverse direction of each boundary element. Although the factor compares lengths, the 'must' criterion reflects the area requirement in ACI 318. This reflects the workshop participants' interest in length of rebar to rather than rebar area to make a decision. However, area requirements must be satisfied. As this area depends on rebar diameter as well as length, listing only length preserves flexibility to consider a different bar size with the same length during CBA's reconsideration phase should the stakeholders not be satisfied with the first alternative selected. The ‘want’ criterion reflects the preference for shorter length, because less length reduces congestion and may be faster to place.

The factor **Number of table bends** refers to the number of table bends in each alternative. There is no ‘must’ criterion for this factor. The ‘want’ criterion expresses preference for fewer table bends, as fabricators prefer to bend bars on an automatic stirrup bender.

The factor **Transverse spacing of bars** refers to the transverse spacing used for each alternative. The ‘must’ criterion states the spacing must meet ACI 318 requirements, which typically limit spacing to 6 in. The ‘want’ criterion reflects the preference for larger spacing to reduce congestion and accommodate concrete flow.

The factor **Room for MEP features** refers to the thickness of the wall relative to the thickness of the boundary element for each alternative. The ‘must’ criterion reflects the fact that the boundary element must be at least as thick as the wall. The ‘want’ criterion expresses preference for a thinner wall than boundary element so MEP features can be “hidden” in the space along the face of the wall between the boundary elements.

The factor **Length of boundary element** refers to the length of the boundary elements of each alternative. The ‘must’ criterion states that the boundary elements must be long enough to contain necessary reinforcement. The ‘want’ criterion expresses preference for a longer boundary element, because this minimizes the length of wall steel that must be placed. Workshop participants wanted to minimize the latter because it can be difficult to keep wall steel evenly spaced.

The factor **Number of hooks** refers to the number of hooks in each alternative. There is no ‘must’ criterion for this factor. The ‘want’ criterion expresses the preference for fewer hooks. Hooks contribute to congestion and take time to bend, so engineers, contractors, and placers alike prefer to use a minimal number of hooks to anchor rebar into concrete.

The factor **Transverse area of steel, A_{sh}/ft** refers to the area of transverse steel per foot in each of the alternatives. The 'must' criterion states the need to meet the area requirements of ACI 318. The 'want' criterion expresses preference for less area per foot in order to reduce congestion.

The factor **Erection stability** refers to the stability of each alternative as the wall is constructed. The 'must' criterion states the requirement to conform to safety regulations (typically governed by height of the wall). The 'want' criterion states the preference for stability, as this makes the job safer and easier to place. Rebar fabricators may choose to add rebar to cages or column spirals to give these elements additional stability. For instance, fabricators may add a diagonal bar from one side of a column cage to another to make the cage more stable during transport and erection. Typically, placers cut these bars out in the field before pouring concrete (Stowers 2008).

The factor **Steel grade** refers to the grade of steel used for each alternative. The 'must' criterion states the steel grade must be at least 60, as this is the most commonly available steel. The 'want' criteria express preference for a higher steel grade in order to relax spacing requirements, and to use the same steel grade throughout the wall, respectively.

8.7.3.2 Determining Attributes of Each Alternative in Each Factor

To begin, the workshop participants used the model and set-based tool (Figure 55) to determine the attributes of each alternative (Table 28).

8.7.3.3 Determining the Advantages of Each Alternative

Workshop participants first identified the least-preferred attribute in each factor (underlined in Table 28) and then determined the advantages of each alternative relative to the least-preferred attribute.

8.7.3.4 Assigning the Relative Importance of Each Advantage

Workshop participants highlighted the most-important advantage in each factor. From amongst the most-important advantages, they then selected the most important one. This most-important most-important advantage is the paramount advantage that is used to establish a scale of importance. The paramount advantage in this case is ‘12 in. thinner than 32 in.’ in the factor ‘Thickness of boundary element.’ This advantage is given an importance of 100 (circled on Table 28). All other importances will be given an importance relative to this.

The workshop participants established importance using the ‘Defender-Challenger’ method, described in detail in Chapter 5. Figure 56 shows a Post-it™ note they used for assigning importance. It lists the factor, and the least-preferred attribute, which will have an advantage of zero. Thus, it shows up at the bottom of the total importance scale (Figure 58).

Figure 57 shows a Post-it™ with an advantage and an importance. The Post-it™ shows the factor, the attribute, and the advantage so participants in the exercise have a means of contextualizing the advantage. Workshop participants listed each advantage on a separate Post-it™, and placed it on the wall. They then discussed tradeoffs between advantages and directed the author to move the Post-its™ up or down on the wall to reflect the relative rank of advantages. Workshop participants thus ordered advantages.

Once they determined an order, Post-it™s were spaced along the wall to reflect the relative importance of each advantage. When participants agreed with the spacing of the advantages, they assigned importance to each advantage.

Figure 58 and Figure 59 show the completed exercise. Workshop participants aligned advantages in each factor vertically. Note this figure shows nine advantages, yet Table 28 shows eleven. After the workshop exercise, the author refined the example to reflect a difference in the number of table bent vs. automatic stirrup bender bent stirrups. This led to the advantage '16 fewer bends' in the 'Number of table bends' factor. Based on discussions at the workshop and afterwards with participants, the author assigned this advantage an importance of 45. Thus, the advantage is a little more important than '10 fewer hooks' in the 'Number of hooks factor,' but is considerably less important than '188 less' in the 'Length of transverse steel' factor. Also, at the workshop, participants approximated values (attributes) for the 'Total transverse rebar area, A_{sh}/ft' factor. The author calculated the actual values after the workshop and assigned importance to align with participant views. Participants approximated the same total transverse rebar area for Wall A and Wall B. They assigned a single importance to this value. The author used that importance (25) for the most-important advantage in the factor ('490 in^2/ft less'), and assigned an importance of 22 to the remaining advantage in the factor ('415 in^2/ft less'). Finally, the author changed one of the factors after the workshop. She changed the factor 'Boundary element thickness – wall thickness' (factor on the far right in Figure 58) to 'Room for MEP features,' due to concern that 'Boundary element thickness-wall thickness' was actually the same as 'Number of corners to form.' The attributes in 'Room for MEP features' remain the same as those for 'Boundary element thickness-wall thickness.' However, the advantage and importance reflect some of the participants' preference for a thinner wall than boundary element to "hide" MEP features.

8.7.3.5 Calculate Total Importance and Make a Selection

After assigning a relative importance to each advantage, participants calculated the total importance of advantages for each alternative. Table 28 shows the results of this calculation: Wall B is the preferred alternative.

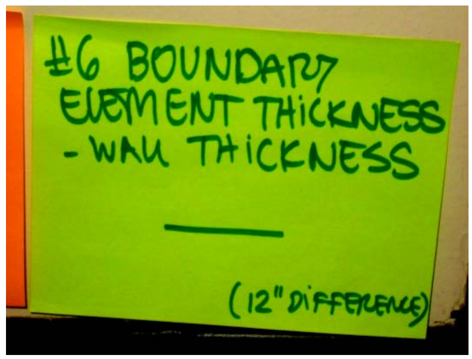


Figure 56. Post-it™ note for factor '6. Boundary element thickness-wall thickness'
(Photograph taken by Kristen Parrish on 4/21/09)

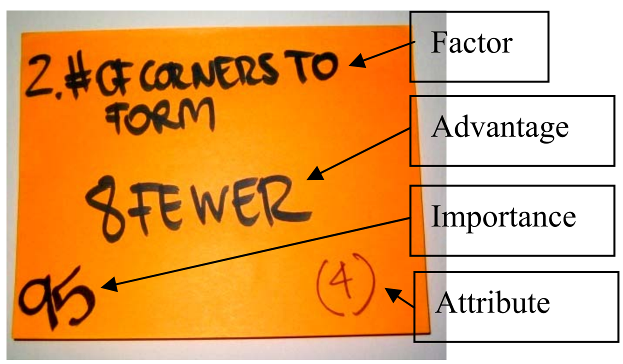
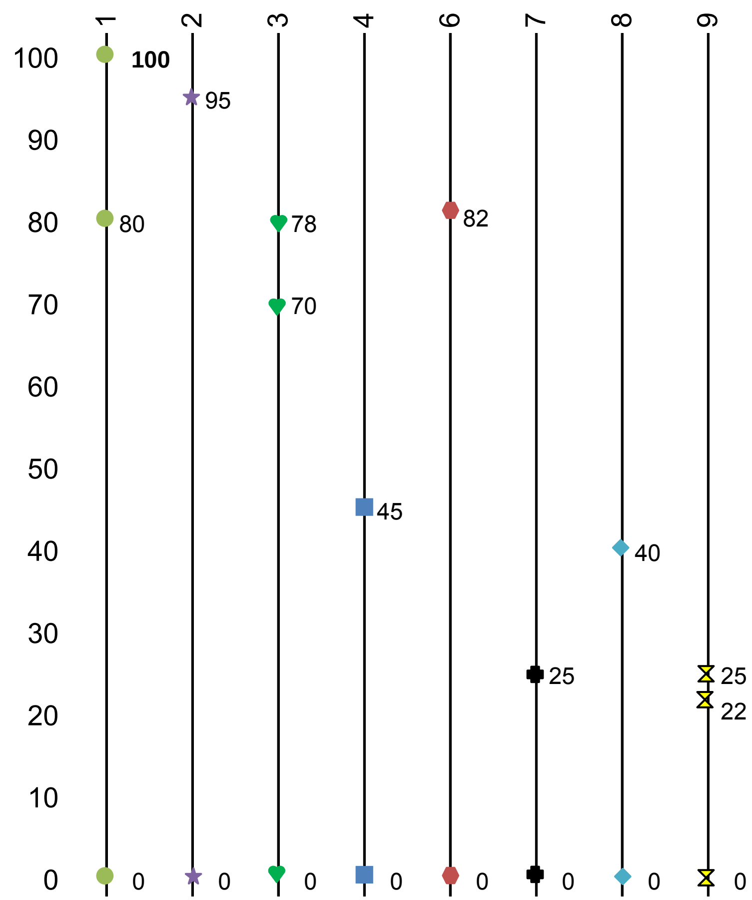


Figure 57. Post-it™ note showing importance of the advantage '0" difference'
(Photograph taken by Kristen Parrish on 4/21/09)

Figure 58. Complete defender-challenger exercise (photograph taken by Kristen Parrish on 4/21/09)

Importance of Advantages



Value	Factor(s)	Advantage(s)
100	1	12 in. thinner than 32 in.
95	2	8 fewer corners to form than 12 corners
82	6	12 in. more than 0 in.
80	1	6 in. thinner than 32 in.
78	3	220 in. fewer than 500 in.
70	3	188 in. fewer than 500 in.
		1.7 in less space than 5.7 in
45	4	16 fewer table bends than 22 table bends
40	8	18 fewer hooks than 28 hooks
25	7, 9	30 in. more than 50 in., 490 in^2/ft less than 1130 in^2/ft
22	9	415 in^2/ft less than 1130 in^2/ft
0		

Figure 59. Importance scale for CBA analysis of shear wall alternatives

8.8 CONCLUSIONS

This chapter described SetPlan and a proof of concept for set-based shear wall design. Using design values from an introductory reinforced concrete design textbook, the author developed a set of possible shear wall alternatives. Using tools including value propositions and SetPlan, the set-based design tool developed jointly with John-Michael Wong, and together with workshop participants, she analyzed the set of shear wall alternatives. Finally, the workshop participants used CBA to select a shear wall alternative. Interestingly, when given alternatives, the workshop participants did not select the same alternative as had been developed in the design textbook (Shear Wall A), as they did not perceive that alternative to provide the best value (measured as total importance of advantages) for the whole project team.

This chapter demonstrated the feasibility of articulating a value proposition for rebar placing in order to support decision-making in the course of a set-based design process. A set-based methodology must be supported by a means to assess and compare stakeholder values, e.g., using CBA. Value propositions clearly show the relationships between design parameters and/or or metrics for value assessment and thus allow for informed conversation. In a point-based methodology, individuals make decisions, often using rules of thumb characterizing what they know of other specialists' concerns. Unfortunately, these do not necessarily reflect relative value, and thus may lead to a decision that is locally optimal, rather than one optimized in light of multiple project stakeholder values. Value propositions are fact-based, contextual to the project, and based on stakeholder-specific capabilities. They focus on relative value of alternatives, and provide more nuance than rules of thumb.

This chapter presented an example of a value proposition, developed in conjunction with San Francisco Bay Area fabricator-placers. Although data used in the numbers presented are fictitious, the trends shown are representative of practices in Bay Area firms. Value propositions will vary from project to project and from stakeholder to stakeholder. For example, a value proposition used by one placer on one project cannot replace that of another placer on another project. However, the trends shown in a value proposition may to some degree carry over to inform future design decisions, much like general estimating data from published books offers first-order cost data. In either case, in design as in estimating, decisions must be based on facts where available, so when pencils are to be sharpened, real people must engage in the conversation, revealing their value propositions based on their own data. These conversations and value propositions can help stakeholders articulate their reasons for considering various factors and criteria during CBA. Further, they can help stakeholders explain their rationale when assigning relative importance to advantages prior to making decisions.

The use of BIM helps project stakeholders develop a shared understanding. BIM models can illustrate alternatives and highlight differences between them. Visualizing these differences offers project teams an opportunity to discuss value tradeoffs associated with them. Visualization also provides a common language for design conversations, eliminating some of the jargon issues between team members. By having design conversations, project teams can make more informed design decisions.

Set-based design requires that project stakeholders collaborate to develop alternatives and subsequently evaluate them. This chapter presented a tool that supplements BIM software with information about rebar fabrication and availability. Tools like SetPlan can help make set-based design feasible in practice, as they help facilitate the development and evaluation of alternatives. However, ultimately, it is conversations between project stakeholders that allow them to explore and evaluate the design space. Set-based design offers a methodological way of exploring the design space to consider multiple stakeholder perspectives.

CHAPTER 9. CONCLUSIONS

9.1 RESEARCH FINDINGS

This dissertation involved literature review, proof-of-concept experimentation, case studies, and action research. At the conclusion of this research, the author postulates answers to her research questions based on the insights offered from the projects and examples presented in this dissertation. Chapter 1 presented the research questions answered next.

9.1.1 OPPORTUNITIES FOR THE APPLICATION OF SET-BASED METHODS TO THE REBAR DESIGN AND DELIVERY SYSTEM

Q1: Given the documented inefficiencies in the reinforced concrete product delivery system, are there opportunities for the application of a set-based methodology for rebar design to the structural design process?

Simply, yes.

Opportunities for application of set-based methods *do* exist in the rebar design and delivery system. When implemented on case-study projects, project teams seemed receptive to the process; they felt it yielded a more collaborative work environment and a better product for the customer. My case-study research showed that set-based methods can be applied to the rebar design and delivery system. The USC project (Chapter 6) highlighted the need to collaborate with rebar fabricators and placers early in the design process to ascertain constructability and avoid rework. The Cathedral Hill Hospital project (Chapter 7) illustrated the need to develop a process to effectively implement set-based design. The shear wall example (Chapter 8) illustrated the use of the proof-of-concept tool, SetPlan, that supports a set-based design process.

The set-based design process is not clearly defined in the literature, so as project teams decide to implement it, they can use the process presented here as a point of departure. Literature suggests that set-based methods could be most effective in design processes where incomplete, but stable, information can be shared early on in an iterative process (Gil et al. 2008; Terwiesch et al. 2002). While set-based design requires early involvement of stakeholders, a question is whom to involve and when. DSM (presented in Chapter 4) helps in this regard: it can highlight where application of set-based methods may be most advantageous. The project team can apply set-based methods to iterative blocks identified in the DSM, develop their own set-based design process, and then implement it on a larger scale.

9.1.2 Insights into the Mechanics of the Set-Based Design Process

Q2: What would a set-based rebar design process *look like*? Each of the questions and answers listed next help develop the mechanics of the set-based design process.

Q2.1: Who should be involved in set-based rebar design?

At a minimum, the rebar fabricator, the placers, the estimators, and the detailers need to be engaged with the structural engineer to effectively implement set-based design. The concrete placer, the general contractor, and the architect also are important stakeholders to work with when performing set-based rebar design, as they have a stake in the rebar placement process. They will therefore add factors, criteria, attributes, advantages, and importance to the CBA table used to evaluate the set of alternative rebar configurations. Owners can encourage set-based design on a project by hiring these stakeholders during the design phase of the project and incentivizing them to use set-based design, e.g., with the Integrated Form of Agreement.

On the USC project (Chapter 6), the general contractor, the architect, the structural engineer, and the owner developed and evaluated a set of alternatives. The structural engineer, Greg Luth, later stated it would have been advantageous to include the rebar fabricator-placer in these early discussions as well, as they were the party responsible for executing the design. (As it stood, the rebar placer joined the project at the end of the Construction Documents phase, about two months before construction began).

Q2.2: At what point in the design phase are set-based methods used?

Set-based methods can be used throughout design. However, as the project progresses, broader alternatives may be eliminated and sets become increasingly detailed. For instance, when the Cathedral Hill Hospital IPD team began using set-based design, they considered concrete and steel as possible building materials. In Schematic Design, they selected steel, thus eliminating the concrete alternative from the set. At the same time, they developed structural system alternatives, so the sets became increasingly detailed after the decision to use steel was made.

Q2.3: What are the levels of detail necessary to define design alternatives?

This question does not have a single answer. Level of detail necessary to define alternatives is a function of how much stakeholders need to know to articulate differences between alternatives so they can evaluate them. Thus, it varies with the stakeholders' ability to determine how to complete their own work to deliver the alternative, the building area, and the project. For instance, a rebar fabricator may need an alternative articulated to a greater level of detail than a mechanical subcontractor to understand how he will fabricate it. The fabricator can thus determine relevant factors and criteria to consider. Level of detail also varies with the building area. For instance, project stakeholders may need more detail to evaluate rebar alternatives in a congested boundary element then they would need to evaluate, e.g., a concrete slab. Level of detail serves the stakeholders' ability to evaluate alternatives, so it is likely to change throughout a project and across projects.

As owners begin to require the use of BIM, project stakeholders may find it easier to generate sets of alternatives with appropriate levels of detail. The Cathedral Hill Hospital project (Chapter 7) highlights the importance of clearly defining the necessary level of detail in design conversations. Articulating necessary detail can avoid rework later in the process due to mis-aligned assumptions (e.g., the beam orientation example presented in Chapter 7). Articulating the necessary level of detail can also eliminate the need for project teams to try to develop detail without enough information (e.g., the wall penetrations example presented in Chapter 7). As project stakeholders gain experience with set-based design, determining the level of detail necessary for a given decision may become more intuitive.

Q2.4: What value tradeoffs are associated with the set of design alternatives?

Value tradeoffs vary with the design phase and project stakeholders. This research illustrates the need to be specific when discussing value tradeoffs so stakeholders can develop shared understanding, use it to evaluate the set of design alternatives, and subsequently make decisions.

CBA (Chapter 5) is a decision-making system that includes methods to evaluate design alternatives and make choices between them. As shown in workshops and described in this dissertation, project stakeholders can document the relative importance of specific advantages, making their value tradeoffs explicit. The topics of value tradeoffs and design decision-making warrant further research.

Q2.5: How do project stakeholders narrow sets of design alternatives?

This research suggests that project stakeholders narrow sets of design alternatives in two ways: through a formal evaluation process or through rules of thumb. Certainly, project stakeholders make decisions in the course of a project; however, this research suggests not all projects develop and implement a formal decision-making process. Some project owners require documentation of decision-making, while others may simply accept the advice of the project stakeholders.

Project stakeholders may wait until the last responsible moment, when failing to make a decision eliminates an alternative, to narrow sets. However, this research recommends that project stakeholders make efforts to formally discuss sets of alternatives and narrow them, following design conversations, and using CBA to evaluate them.

This research illustrates that sets contract throughout design, but the level of detail expands. Initially, the design space is large though defined only in the abstract, and through Schematic Design, project stakeholders narrow it by deciding which schematic design to pursue. Then, the set of alternatives available in Design Development expands at a different level of detail. For instance, initially, project stakeholders may decide on a building material (e.g., steel or concrete). In selecting a building material, they reduce the schematic design set to steel. During Design Development, they consider a more detailed set of steel structural systems. As design progresses, the set becomes increasingly detailed, but it does not expand. That is, project stakeholders avoid backtracking, because they avoid eliminating alternatives too early in the design process.

Figure 60 shows small dot that represents an alternative. The size of the dot illustrates its level of detail. That is, the dot larger as its level of detail increases. Project stakeholders develop increasingly detailed alternatives while avoiding backtracking. Thus, the design space narrows while the level of detail expands.

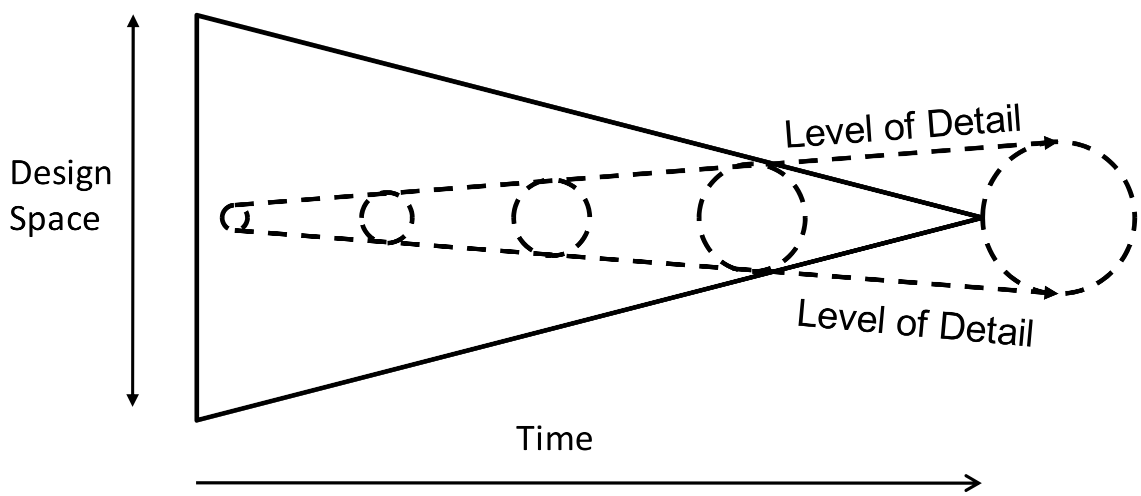


Figure 60. Evolution of sets during set-based design

Q2.6: How should stakeholders make design decisions in a set-based design environment?

The author also investigated four group decision-making systems, outlined in Table 4. Specifically, she researched Multi-Attribute Utility Theory, the Analytic Hierarchy Process (AHP), CBA, and Robust Decision Making. She compared AHP and CBA through example. Based on the author's research to date, CBA was found to be the only sound method available for making multiple-stakeholder decisions, and should thus be used.

Practitioners involved in this research, engaged both through workshops and case studies, have praised the use of set-based design on their projects. They reported exploring the design space by developing alternatives inspires confidence in the project team that the alternative selected is the best for the project. Further, exploring the design space facilitates project stakeholders developing a shared understanding of the project, as each stakeholder benefits from the expertise of others and challenges others' the paradigms (Lichtig 2005b).

9.2 CONTRIBUTIONS TO KNOWLEDGE

Table 29 outlines contributions to knowledge from each case study and the shear wall example. The bold headings represent initial research goals, and the italicized headings highlight specific research deliverables.

9.2.1 CATALOG OF STRUCTURAL DESIGN METHODOLOGIES

The author's literature review and practitioner survey catalog, respectively, structural engineering design methodologies developed in the literature and those used in practice. Table 3, Table 15, and Table 16 present the findings from these efforts. These tables presented taxonomies that can serve as a point of departure for future researchers exploring and developing design methodologies.

Table 29. Contributions to knowledge from each case study and the academic example

USC	Cathedral Hill Hospital	Academic Example
Develop a set-based methodology for rebar design		
Determine level of detail necessary to define a set		
	Illustrate the importance of decision units and communication	Show a set of alternatives for a given set of design parameters
Determine how sets are narrowed		
Determine when sets are narrowed and the factors and criteria used	Determine when sets are narrowed and the factors and criteria used	Discuss why alternatives are eliminated from sets
Select a decision-making process to use		
Discuss who is involved in decision-making at a given project phase	Explore the use of CBA for this project	Use CBA to select a shear wall from a set of alternatives
Develop an A3 report		
	Example A3s from current practice	
Develop a software tool for set-based design		
Determine decision unit used in software		
Report on change in BIM capabilities throughout this project		Illustrate how SetPlan aids in evaluating a set of alternatives
Representation of objects in software		
		Color code a BIM to reflect bending capabilities
Analyze value added by the software		
How are opportunities for prefabrication determined?		Discuss how software supports design conversations
Write proof of concept for software		
		Show software capabilities by example
Document the use of set-based design on case study projects		
Select case study projects		
Document set-based methodologies used		
Document the use of set-based design in current practice	Document the use of set-based design in current practice	Provide proof of concept for set-based design methodology
Compare set-based design to point-based design on project		
Determine metrics that define success in each project		
Discuss difference in bar lists generated by GPLA to those generated by Fontana	Discuss evolution of set-based design process at Cathedral Hill	
Collect Data		
Write papers for conferences and journals		
	Construction Research Congress 2009 paper; IEEE Transactions on Engineering Management paper in development	IGLC 17 paper

9.2.2 DOCUMENTED THE USE OF SET-BASED DESIGN ON CASE-STUDY PROJECTS

Chapter 6 and Chapter 7 presented case-study projects that used set-based design to some degree. Documenting these case studies serves two purposes. First, documentation supports dissemination of findings, which in turn supports other researchers' and designers' understanding of how set-based methods have been applied in the AEC industry. Readers of this dissertation may review set-based design implementation strategies used in case studies to extract new theories and formulate new hypotheses about types of projects where set-based methods can add the most value, design phases where set-based methods are most difficult to pursue, etc.

Second, case studies informed the development of the academic example, which merges 'best practices' from each case study into a single process. For instance, one lesson learned from both case studies is that the set-based design process can be overwhelming to implement for every decision unit on a project. Thus, for the academic example, the author selected a shear wall as the decision unit, which has enough complexity to illustrate the benefits of SetPlan, stakeholder collaboration, and evaluating sets with CBA, but is a small enough decision unit to be 'solvable.'

Practitioners involved in this research, engaged both through workshops and case studies, have praised the use of set-based design on their projects. They reported exploring the design space by developing alternatives inspires confidence in the project team that the alternative selected is the best for the project. Further, exploring the design space facilitates project stakeholders developing a shared understanding of the project, as each stakeholder benefits from the expertise of others and challenges others' the paradigms (Lichtig 2005b).

9.2.3 PROOF OF CONCEPT FOR A SET-BASED METHODOLOGY FOR REBAR DESIGN

The primary contribution of this research is the development of a set-based methodology for rebar design. Set-based methodologies exist and are used in various industries, including the AEC industry (e.g., USC project and Cathedral Hill Hospital project). However, the author is not aware of an example of set-based rebar design. Chapter 8 presented a set-based rebar design example. It illustrated level of detail necessary to define a set of alternatives and a decision-making system that evaluates this set of alternatives. The academic example also illustrated how software tools can support a set-based methodology for rebar design.

9.2.4 PROOF OF CONCEPT FOR A SET-BASED DESIGN SOFTWARE TOOL, SETPLAN

Currently, 3D BIM software offers users specific reinforcement configurations to insert into structural elements during detailing. Users can modify these configurations, but BIM tools initially draw a specific rebar configuration. SetPlan aids designers in evaluating sets of design alternatives; however, it does not generate these sets. It allows project teams in the course of design to compare detailed elements by highlighting differences between them in terms of their ability to be bent with an automatic stirrup bender. Further, it highlights information about specific bars in the dashboard.

Information shown on the dashboard makes explicit knowledge that is otherwise implicit in “rules of thumb” and “design experience.” This supports project stakeholders developing a shared understanding of stakeholder values which in turn facilitates more effective design conversations. Moreover, the tool breaks down ‘language barriers’ in the industry by allowing stakeholders to *see*, rather than talk about, alternatives. Although the data presented in the tool is fictitious, it could be updated to reflect actual data for a project. Finally, this tool, and others that could be developed like it, can reduce the time investment necessary to practice set-based design by automating some of the tasks necessary to evaluate sets.

SetPlan loosely integrates with Tekla Structures 14.0 in that it searches the Tekla Open API specifically. However, it searches for objects available in other 3D BIM models (e.g., rebar, concrete columns, etc.), so with modification, SetPlan could interface with other BIM software programs, including AutoDesk Revit. The developers of SetPlan did not intend for it to interface with detailing software (e.g., RebarCAD) or structural analysis software (e.g., RISA), as they view BIM models as the easiest vehicles for illustrating and comparing alternatives.

9.3 CROSS CASE-STUDY CONCLUSIONS

After reviewing the two case studies and the academic example, common lessons stand out. The following sections describe each of these lessons in detail.

9.3.1 THERE IS NO SUCH THING AS A 'TYPICAL SET-BASED DESIGN PROCESS'

Set-based design, as practiced at Toyota, is has not yet been described in the English literature in a manner that is conducive to applying it 'off the shelf.' Kennedy (2003), Kennedy et al. (2008), Liker (2004), Liker et al. (1996), Morgan and Liker (2006), Sobek II et al. (1999), and Ward et al. (1995) refer to it as a new product development process that postpones commitment until considering multiple stakeholder wants and needs. Even where they provide specific examples, it is unclear exactly how developed the set of alternatives was before engineers at Toyota "locked it" and began evaluation. Further, the essence of set-based design seems to be the synergistic relationships it sparks between project stakeholders and the products resulting from these synergies. Literature cannot prescribe a set of steps to implement a set-based design process, since it is context-specific. It varies with the stakeholders involved, the design phase, the decision unit, and the project itself.

A project team keen on implementing set-based design must thus tailor the set-based design process presented in this dissertation to their project and stakeholder needs. The project stakeholders can work within their set-based design process to create the synergistic relationships that seem inherent to Toyota's product development process. This will require stakeholders to develop new working relationships rather than adversarial ones and think in terms of sets rather than points (as seems to be today's industry standard). As with any new process, this one will offer new opportunities to improve the 'status quo.' Project stakeholders can collaborate to make the process fit their specific needs. Similar to the case of the Cathedral Hill Hospital Project, as the stakeholders become accustomed to new working relationships and processes, they will refine the process to suit their unique needs and realize the rewards of a collaborative work environment.

9.3.2 SET-BASED DESIGN MAY BE MORE EFFECTIVE FOR SOME DECISION UNITS THAN OTHERS

Stakeholders starting to use a set-based design process may want to develop it on a small pilot project (or piece of a larger project), refine it, and then begin to implement it on a larger scale. To determine what to use as a pilot project, they may use DSM to find an iterative block and then apply a set-based design strategy to the activities within it. Set-based design may release some dependencies in the block, thus removing some negative iteration. Set-based design strategies may be most effective in these iterative blocks, i.e., successive activities may be able to begin earlier by considering sets rather than points.

Project stakeholders can assess an iterative block to determine whether the process defined by the block is uncertain or ambiguous (Schrader et al. 1993). If the stakeholders determine the process is uncertain, implementing set-based design may improve the process. Otherwise, set-based design may not release dependencies, and thus, may not make significant process improvements.

9.3.3 TOOLS MAKE SET-BASED DESIGN EASIER TO IMPLEMENT

Set-based design requires developing a set of design alternatives rather than a single design point. Therefore, it seems logical to believe set-based design will take longer. If that were true, project stakeholders may be reluctant to spend more time developing alternatives when only one will eventually be built. However, in developing alternatives, project stakeholders often develop innovative solutions they may not have had time or incentive to develop otherwise. The case studies suggest set-based design is worth the effort; it reduces rework later in the process and it fosters innovation and collaboration on projects. This research suggests set-based design can actually *save* time on a project, as it brings constructability issues to the fore in design, and thus reduces rework in construction.

Tools that help project stakeholders generate and evaluate alternatives provide support for set-based design, and reduce the time investment necessary to implement it. Workshop participants involved in this research applauded the development of these tools and stated that they would make set-based design more attractive to practitioners. Indeed, workshop participants seemed to ‘latch on’ to the example of scheduling a meeting with set-based design (e.g., using www.doodle.com), which convinced them of its merits for AEC applications. As BIM use increases in the AEC industry, and related tools become more versatile and sophisticated, project stakeholders may find it easier to develop sets of design alternatives, and may thus be more inclined to use set-based design.

9.3.4 DESIGN *IS* A SOCIAL PROCESS

Design is a social process, and as such, the conversations determine the outcome of the design process. Ultimately, it is understanding, sharpened by design conversations, that makes a design process and product better. Set-based design requires collaboration among stakeholders, both to develop sets and to evaluate them. Thus, it prompts stakeholders to engage in design conversations. Lean tools and processes often help facilitate these conversations; however, each of the case studies emphasizes that no tool or process can be an effective substitute for conversation.

9.4 FUTURE WORK

Numerous opportunities exist for future research into set-based design, including research to more formally define it. The author highlights the need to expand on tools available to aid in set-based design and to further understand AEC design methodologies in support of developing design methodology theory, especially as it relates to set-based design.

9.4.1 FURTHER DEVELOPMENT OF SET-BASED DESIGN TOOLS

Case studies highlight the benefit of tools that help implement set-based design, whether they be technological (e.g., BIM software) or process-based (e.g., A3 reports).

BIM technology makes rapid development of alternatives easier. BIM tools can illustrate different levels of detail at different design phases. Further, BIM models can show different levels of detail in different areas, e.g., designers can choose not to detail a beam, but detail a wall in the same model. A tool that works with BIM software to communicate design values yet postpone commitment to *a specific object* may aid in set-based design implementation. For example, if a user could specify a rebar area requirement within a reinforced concrete object, and block out space for it, yet not commit to a specific configuration at that time, the designer could essentially define a set without enumerating each instance of it. Rather, instantiation could be postponed until project stakeholders feel they have ample information to commit to a specific rebar configuration.

Process-based tools like A3 reports and DSMs, and decision-making systems like CBA help to implement a set-based design process. Though not created specifically to serve (or even support) set-based design, they make implementation easier. These tools support organizational learning, so lessons can be carried from project to project. For instance, an A3 report could capture alternatives generated on one project, and then the stakeholders could use that same set of alternatives on a future project. In fact, this happens regularly at Toyota. Likewise, DSMs may highlight opportunities for set-based design, and when the stakeholders face the same iterative block on another project, they could again implement set-based design. The author recommends articulating a need in the set-based design process, e.g., to document alternatives, then explore the organizational tools available to find a fit. That is, develop a pattern of use for a tool in support of the set-based design process. Similarly, CBA tables can be reused from project to project, and stakeholders can develop lists of company-specific factors and criteria based on their capabilities.

The question of how to augment BIM with process-based tools warrants future research.

9.4.2 Develop a Greater Understanding of the Theory of Design Methodologies

Theory postulates causal relationships, and can thus guide future development of design methodologies. Without an understanding of the underlying theory of design methodology, it is difficult to predict how changes to the design process will affect it. For the moment, case-study research seems the best course of action to understand how changes to the design process impact projects. Researchers can begin to understand the impacts of changes to design methodology, beyond the case-specific level, by looking for trends across cases. They can thus provide a platform for understanding design methodologies in practice and developing improvements.

9.4.3 Develop a Theory of Set-Based Design

Similar to the need to gain a greater understanding of the theory of design methodologies so they can be improved, a theoretical understanding of set-based design may reveal opportunities for improving and implementing it. This dissertation provides a proof-of-concept for set-based design. Based on this research, it seems that set-based design should be implemented on a small scale, the process refined, and implementation expanded as necessary or desired for a project. As researchers continue to learn based on case studies, they can develop a theoretical understanding of set-based design and gain insights into how it works in practice. Understanding theory provides a lever for changes; that is, knowledge of causal relationships enables people to better predict the results of these changes. Thus, future researchers can begin to improve the set-based design process.

9.5 CONCLUSION

Research presented in this dissertation applied set-based design, a methodology developed by engineers at Toyota, to reinforced concrete and specifically the rebar design and delivery system. It demonstrated that set-based design cane effective in this application.

We expect set-based design can be applied more broadly to other products in the AEC industry based on case-study findings. Future work is necessary to develop this process for the broader AEC industry, which incorporates multiple stakeholders in various projects.

Developing set-based design theory will allow practitioners to realize design process improvements from its implementation. The set-based design process could eventually be used to spur innovation beyond the product-level of design projects; indeed, it could yield innovation in design and construction methods.

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APPENDIX A. A CURRENT-STATE CROSS-FUNCTIONAL DIAGRAM OF REBAR DESIGN AND DELIVERY

Iris D. Tommelein[1], Glenn Ballard[2], and Kristen Parrish[3]

A.1. INTRODUCTION

Many engineering and business processes in project delivery are complex, even wicked (Lane and Woodman 2000). Exactly how complex is hard to describe, yet, coming to grips with at least some aspects of this complexity is a necessary step towards purposefully designing production systems and improving their performance. This report builds on research by Tommelein and Ballard (2005) that was conducted jointly with an industry task force, detailing the need and desire for changes in the concrete reinforcing steel (rebar) industry. Figure 1 shows the task force's strategy for restructuring the rebar supply system framed by descriptions of the current state and the desired future state, and taking into account obstacles that stand in the way of making the change from present to future.

As a contribution to the development and study of theory and principles that support the design and management of project-based production systems, this report focuses on the delivery of rebar that is used in structures made of concrete. To limit the scope of this work at this time, the study documents only the 'flow' of rebar, while omitting other 'flows' needed to support concrete construction taking place in parallel and being

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intertwined with the flow of rebar (e.g., flows of formwork, concrete, labor, equipment, embeds, etc.).

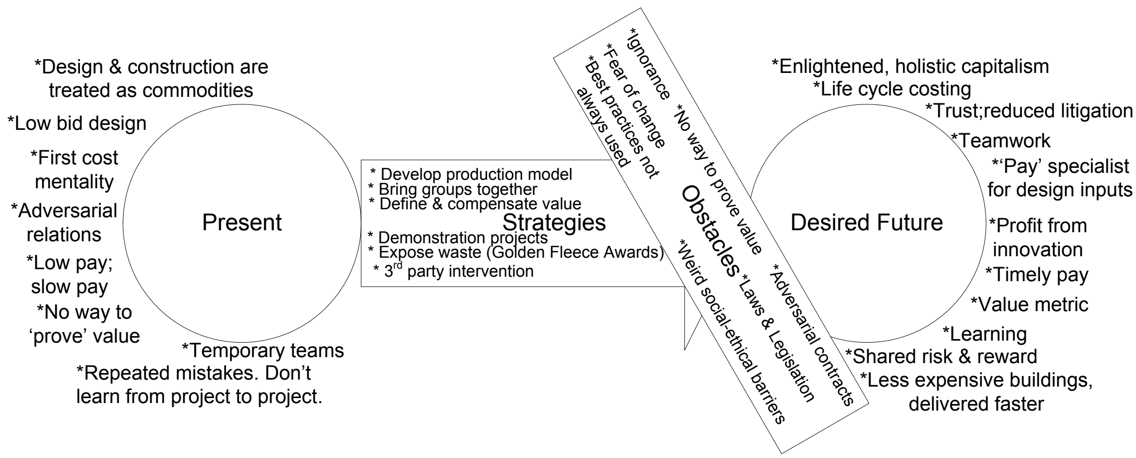

Figure A1. Task Force strategy (Figure 1 from Tommelein and Ballard 2005)

Many stakeholders are involved in the rebar delivery process. This report focuses on those stakeholders directly related to the manufacturing, design, fabrication, inspection, and placement of rebar—'direct stakeholders'—as shown on the left-hand side of the cross-functional diagram presented later (Figure A5). Other parties undoubtedly have vested interests in rebar delivery.

A.2. PROCESS MAPPING

A.2.1. DEFINITION OF PROCESS MAPPING

Process mapping is a method used to visualize the flow of material as well as the links between and beyond the single process level (Rother and Shook 2003). Examples of process mapping methods include value stream mapping (Rother and Shook 2003; Womack et al. 1990a) and the development of cross-functional maps or swimlane diagrams (Damelio 1996). Process maps can show the flow of material and information from customer order through customer delivery; they can facilitate the identification of waste and its root causes (Arbulu and Tommelein 2002). “Cross-functional maps [swimlane diagrams] illustrate how work gets done in organizations” (Damelio 1996). This report presents a cross-functional diagram to illustrate flows of information and material between direct stakeholders in the rebar supply system (these stakeholders are shown in the “lanes” of the diagram).

Cross-functional diagrams differ for different project types (e.g., residential vs. highway construction vs. marine construction) because design and construction methods differ from one sector of the industry to another, and even within sectors. For instance, commercial projects may require the use of a tower crane to hoist rebar to different floor levels, but residential projects seldom do. The procurement process may vary with material, so cross-functional diagrams may also vary with material. For example, a cross-functional diagram showing construction with #3 bars (e.g., used in single family home construction) may look different than a cross-functional diagram showing construction using only bars larger than #3. Some rebar mills (mini-mills) do not roll #3 bars because it is too difficult to roll on the equipment used for larger bars, so the cross-functional diagrams would reflect this difference. Cross-functional diagrams may also differ for different contract structures, as responsibilities may shift to different members of the supply chain. Maps also differ regionally, e.g., industry practices on the west coast of the United States differ from those on the east coast, and practices in other countries differ from domestic practices (Polat and Ballard 2005a; 2005b).

Further, the materials used to make rebar span quite a range and continue to be developed. Outside the scope of this report are the delivery processes for specialty rebar such as epoxy-coated rebar, low carbon rebar, galvanized steel, ASTM A 995 special corrosion resistant or controlled magnetic permeability steel bars, as well as welded-wire fabric. Given the variety of practices, even within a limited scope that focuses on rebar delivery, the cross-functional diagram presented here documents a current state of practice but is in no way unique or does it exactly pertain to any one specific practice.

A.2.2. RELATED WORK

Polat and Ballard (2003) documented information and material flows in the Turkish rebar supply chain. They developed five process maps to illustrate the different workflows practiced in Turkey. The mapping efforts revealed waste in the supply chain, and allowed root causes to be examined. They found a lack of trust between members of the supply chain to be a cause of waste in that supply chain. Polat and Ballard further explored the Turkish rebar supply chains to find opportunities for prefabrication (2005a; 2005b; 2006). However, their research showed that prefabrication was often undesirable in Turkey due to long lead times for prefabricated pieces and high shipping costs.

Hu (2003) used value stream mapping to analyze the rebar supply chain in China. Hu found the lack of integration across interfaces of the supply chain led to waste, and suggested integration of the supply chain and coordination amongst supply chain members as means to reduce that waste. Chin (2005) used process mapping to understand lead times in the rebar delivery system. Based on the findings of the value stream map, Chin suggested changes to the detailing and Request for Information (RFI) processes to reduce lead times in the rebar delivery system.

Mapping has been used to characterize a variety of construction industry practices, e.g., Tommelein and Li (1999) described alternative means for ready-mix concrete delivery, and Tommelein and Weissenberger (1999) described the location of buffers in the structural steel supply chain. Mapping also has been used to identify opportunities for implementation of lean construction practices outside of the rebar industry. Arbulu and Tommelein (2002) studied the supply chain for pipe supports in power plants. Based on the value stream map created in their 2002 case study, they suggested improvements to the pipe support supply chain to reduce waste (Arbulu et al. 2003). Improvements include partnering with suppliers, standardizing the work products and processes, fostering a collaborative and communicative project environment, minimizing batch sizes, and dedicating resources where appropriate. Tuholski (2008) mapped the structural steel supply chain to identify iteration blocks and suggested strategies to reduce unwanted, so-called ‘negative’ iteration (Ballard 2000c). He found that eliminating a competitive bid process can reduce the need for rework in design, and a collaborative approach will generally reduce negative iteration in a process.

A.3. OBJECTIVES OF THIS MAPPING EFFORT

The objectives of the mapping effort of rebar delivery, described in this report, are manifold:

1. Lay out a current state of practice in rebar delivery (in line with Tommelein and Ballard (2005)
2. Solicit industry input and deepen understanding of current and evolving practices, and their drivers.
3. Provide novices and industry entrants an understanding of complexity, specialization, and fragmentation of industry, including handoffs to whom and when, as well as rework cycles.

4. Provide a basis for research by us and others by identifying steps to take in order to get from the present to the desired future state, e.g.,
    a. identify opportunities where collaboration might be most useful
    b. highlight business opportunities (make or buy decisions, boundaries of firms)
    c. expand on the map to include process times and more detail in order to get to a value stream map that allows for identification of value-added time vs. non-value added time, followed by waste elimination efforts.
    d. Detail production system characteristics (inventory management approaches using kanban, min-max replenishment, etc.)

A.4. CONTRACTUAL STRUCTURES IN REBAR DELIVERY

Figures A2 and A3 depict contractual relationships and information flows between the direct stakeholders considered in this report. Figure A2 represents a "traditional" structure where the architect holds a contract with the owner and the general contractor holds the prime contract with the owner. Figure A3 represents a structure where the structural engineer holds the prime contract with the owner. The cross-functional diagram presented in this report is valid for either contract structure.

In both figures, lines without arrowheads represent contracts. The black box around the rebar placer, the rebar fabricator, the detailer, and the estimator shows that in some cases, all four of these parties are housed within one firm, here referred to as a fabricator-placer. However, this is not always the case, as depicted by the dashed lines that connect the general contractor to the rebar placer and rebar fabricator, and by the dashed lines that connects each of the four entities to each other. Contract Scheme 1 shows the contractual relationship with a fabricator-placer (common on the west coast of the United States) and

Contract Scheme 2 shows the contractual relationship with a separate rebar fabricator and rebar placer.

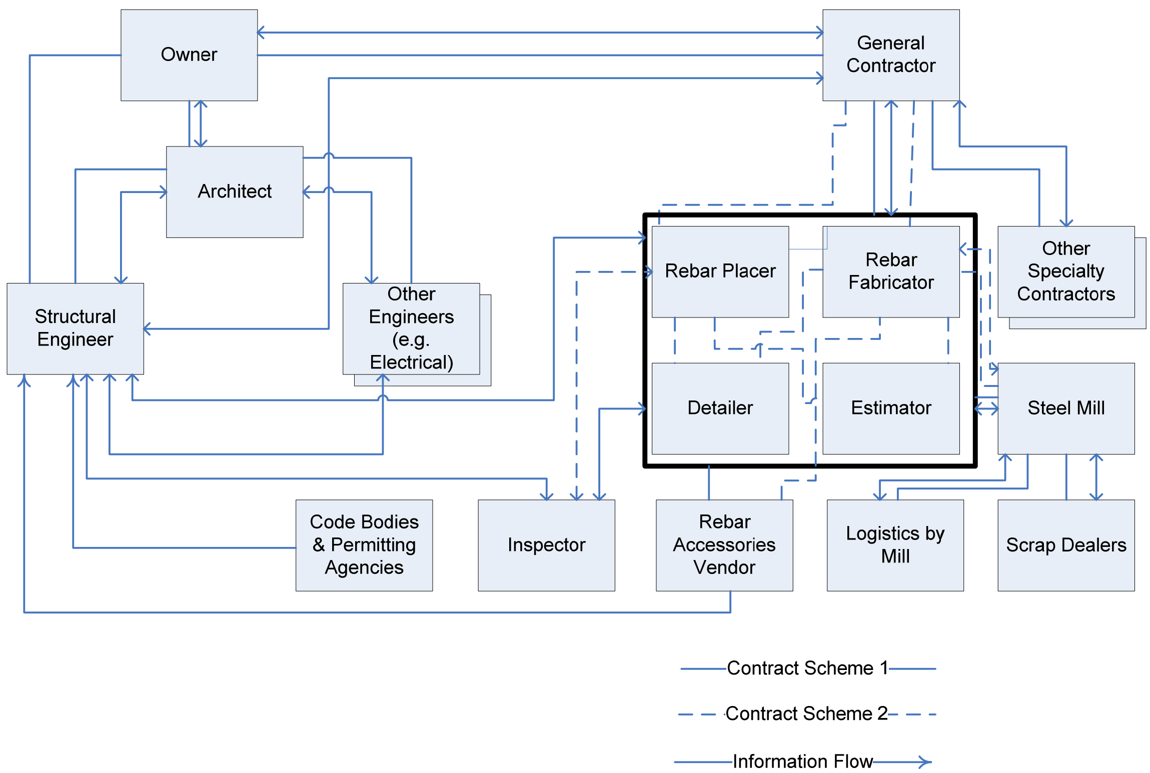

Figure A2. “Traditional” contract structure

Figure A2 details the “traditional” contract structure in which the owner contracts with an architect and separately contracts with a general contractor. The architect then contracts with all engineering- and other design specialists. The general contractor contracts with all necessary specialty contractors and suppliers. In this contract structure, the owner directly exchanges information with the architect and general contractor. Information flows from the owner to the other entities shown in the figure is assumed to be indirect.

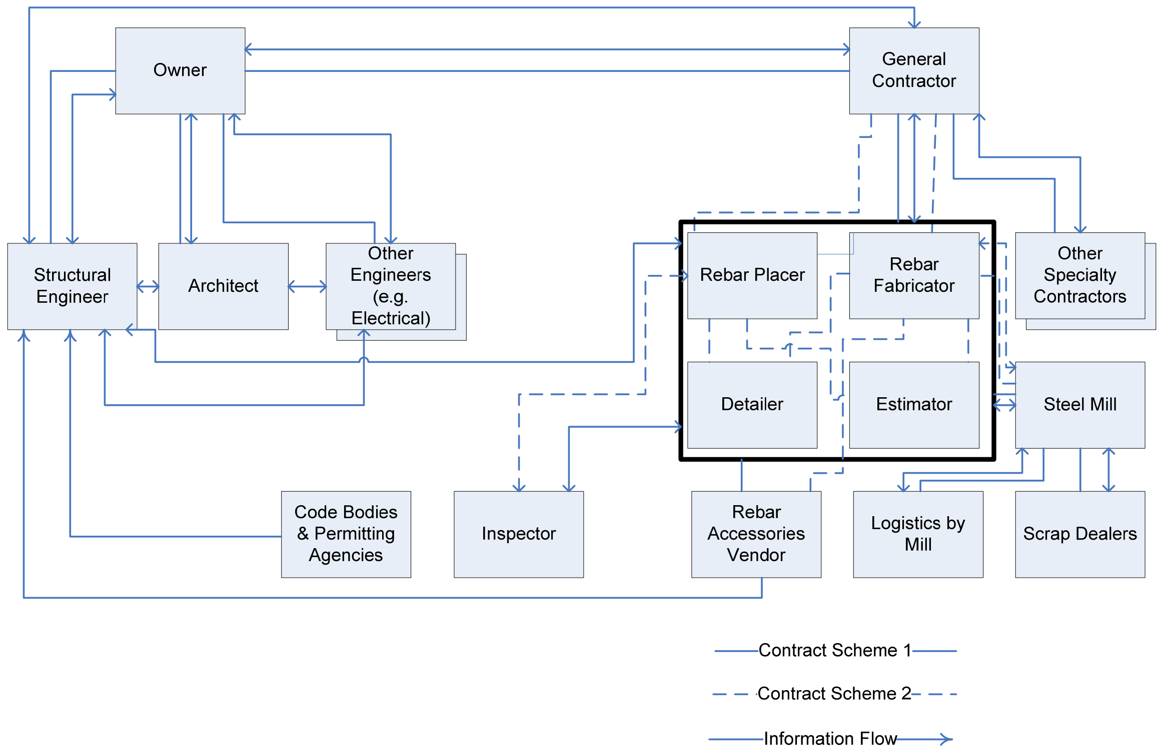

Figure A3. Structural Engineer-Primed contract structure

Figure A3 details the SE-primed contract structure in which the owner directly hires the structural engineer. In this contract scheme, the owner exchanges information directly with the structural engineer, as well as with the architect, the general contractor, and the other engineers. Information flows from the owner to the subcontractors is assumed to be indirect.

Both figures show information flows with a curved headed arrow. Note that information flows from the rebar accessories vendor(s) to the structural engineer, but the rebar accessories vendor(s) contracts directly with either the rebar fabricator or the rebar fabricator-placer. Information also flows back and forth between the structural engineer and the architect, and between the structural engineer and the other engineers. A two-directional information flow is shown between the fabricator-placer and the structural engineer. If the rebar fabricator is separate from the rebar placer, the structural engineer would share information with *each* of these entities (not shown in the figure). Two lines (one with a two-directional arrow and a one solid line without arrows) are shown between the fabricator-placer and the steel mill. The steel mill would contract and exchange information with a rebar fabricator if the fabricator and placer were separate, as denoted by the dashed lines (one with arrowheads and the other without, to represent information exchange and a contractual agreement, respectively). The inspector is also shown exchanging information with the fabricator-placer (solid line with arrowheads). If the fabricator and placer were separate, the inspector would share information only with the placer, as denoted by the two-headed dashed line. The general contractor and the structural engineer also exchange information in both figures.

A.5. CROSS-FUNCTIONAL DIAGRAM DETAILS

A.4.1. DIRECT STAKEHOLDERS CONSIDERED

This cross-functional diagram considers the following direct stakeholders:

- **Scrap Dealers:** This includes the Scrap Peddler, the Scrap Broker, and the Scrap Processor. All are housed in this lane of the map to limit the height of the map. The Scrap Peddler buys scrap from multiple sources and sells it. The Scrap Broker sets up agreements to sell the scrap to one or multiple customers and arranges shipping. The Scrap Processor blends scrap to achieve a desired mix.

- **Rolling Mill:** The steel mill on this map refers to a mini mill. A mini mill consists of a melt shop for scrap melting and billet casting and a rolling mill to roll specific bar sizes and lengths (Wikipedia 2007).

- **Logistics by Rolling Mill:** This swimlane represents the shipping of rebar from the mill to either directly to a fabricator or to a warehouse who subsequently sells the rebar.
- **Structural Engineer:** Structural engineers are licensed professionals (engineer of record) who work in conjunction with owners and architects to develop a reinforced concrete structure that meets the project's needs while at the same time satisfying structural performance requirements mandated by structural codes and permitting agencies.
- **Architect:** The architect makes decisions that impact the rebar delivery process, such as the initial layout of columns, the size of walls, and the architectural details (such as façade elements) of the structure. After architectural concepts are developed (shown on drawings or in a Building Information Model), the structural engineer uses these as inputs for structural design. Structural engineers, owners, and architects iterate through different design alternatives until a design is developed that is acceptable to all of them.
- **Owner:** The owner commissions the design and construction of a structure and selects a team to perform these tasks. Typically, the owner prescribes a function for the structure, which serves as input to the architectural and structural design. The owner works with the architect, the general contractor, and others to ensure the structure designed and built meets the owner's use requirements.
- **General Contractor:** The general contractor is responsible for subcontractor selection and development of a master schedule for the project. The general

contractor typically handles construction management, including site preparation and cleanup, and communication with the owner and architect. In some cases, the general contractor may also perform some of the work onsite.

- **Crane and/or Rebar Placer:** 'Crane' refers to means needed to handle rebar. Rebar handling is managed by the rebar placer who is responsible for placing bars onsite in accordance with the placing drawings developed by the detailer. The placer may or may not use a crane (e.g., their own or the general contractor's) to fill this need.

- **Fabricator:** The fabricator is responsible for cutting and bending rebar in accordance with the placing drawings. This often involves bending ties or hooks in the fabrication facility. The fabricator is also responsible for shipping material to the job site.

- **Detailer:** The detailer is responsible for creating placing drawings (Concrete Reinforcing Steel Institute 2002). These drawings show how to place each bar specified in the structural drawings. Many structural drawings show "typical details." The detailer converts these typical drawings into more specific drawings that illustrate exactly what bars need to be placed where and how they must be bent. If the rebar detailer is not an employee of either the fabricator or the placer (or fabricator-placer), s/he will likely be hired directly by the fabricator, as their drawings show the necessary bar bends and lengths.

- **Estimator:** The estimator is responsible for developing a bid for the rebar subcontract. The estimator may be employed by the fabricator or placer (or fabricator-placer). If the estimator is not an employee of the fabricator or placer (or fabricator-placer), the estimator would be hired by the rebar fabricator and the rebar placer to develop a bid for the fabrication and placement, respectively. On large projects, two estimates are often developed for fabrication and two for placement. The first is done by an in-house estimator, and the second by an independent estimator. The fabrication estimates are compared and reconciled to ensure the fabricator or placer (or the fabricator-placer) does not grossly underbid the job. The placing estimates are also compared and reconciled to ensure the placing contract is not grossly underbid.

- **Code Bodies/Permitting/Testing Agencies:** Code bodies, permitting agencies, and testing agencies each may play a role in construction projects. Code bodies are rarely directly involved on a specific project, but codes adopted by a given city, county, state, or country determine what is and is not permissible structurally. This is an important issue in tall buildings, where structural codes can become very stringent and structural design needs to be creative. Permitting Agencies are responsible for checking design drawings, construction sites, and construction progress before issuing permits granting (continued) construction or occupancy. Permitting agencies in this map include both the local building offices responsible for checking structural plans and the inspection agency responsible for checking rebar installation onsite prior to concrete pours. Testing agencies may test materials when the contractor or engineer is required to do so by the code or permitting agency. Note that code bodies, permitting agencies, and testing agencies are all independent agents.

- **Accessories Vendor:** The accessories vendor supplies rebar accessories, such as embeds, couplers, and mechanical splices to the rebar placer (or fabricator-placer).

Figure A4 introduces the symbols used in the cross-functional diagram shown in Figure A5.

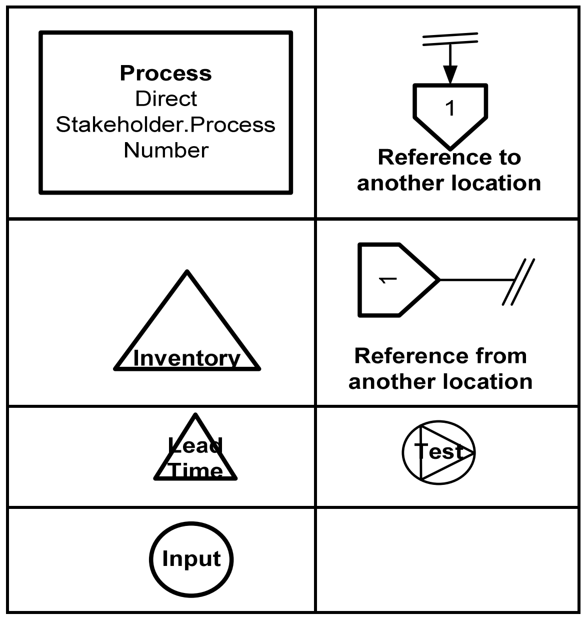

Figure A4. Symbols in cross-functional diagram

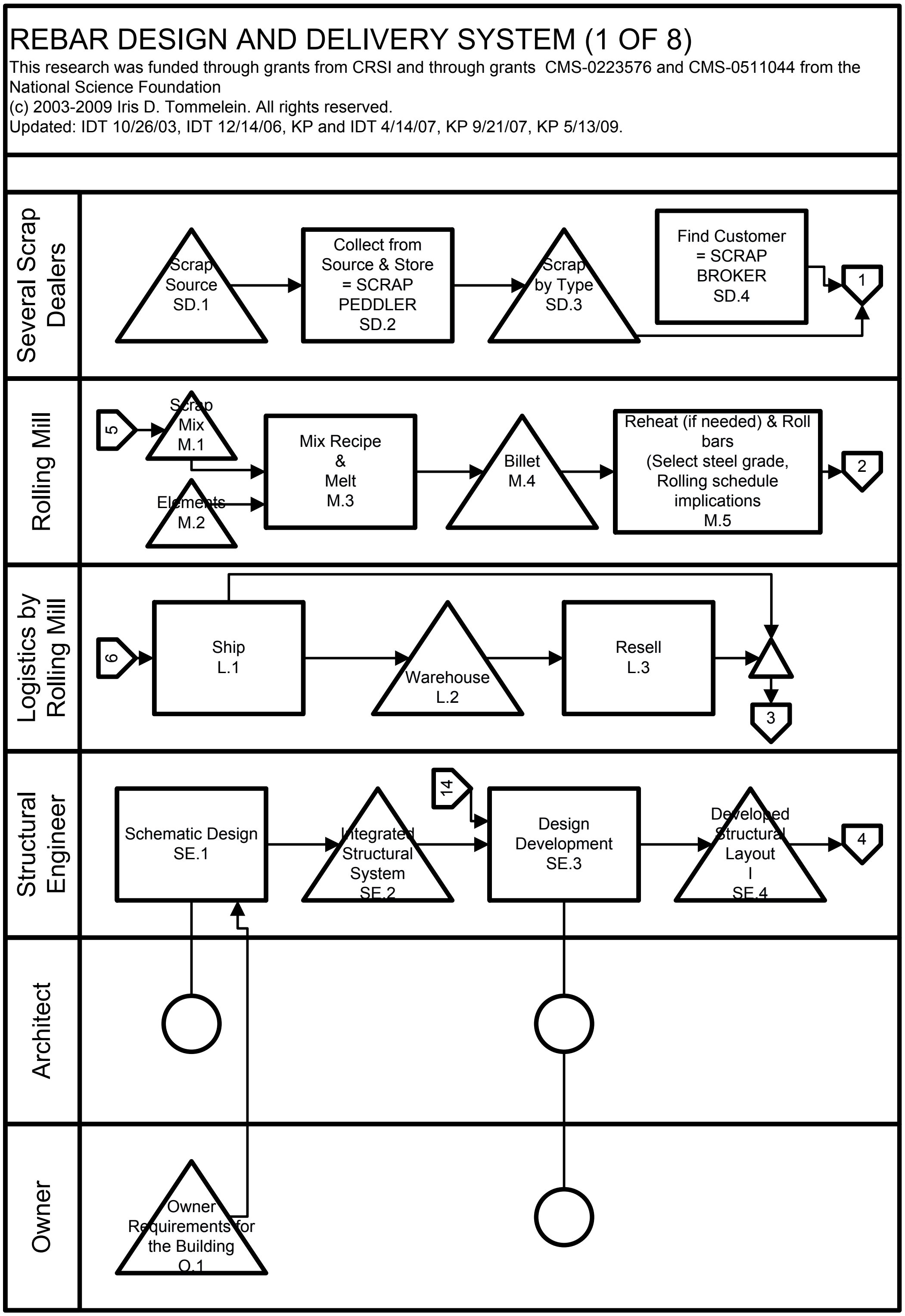

Figure A5 (1 of 8): Cross-functional diagram of the rebar design and delivery system

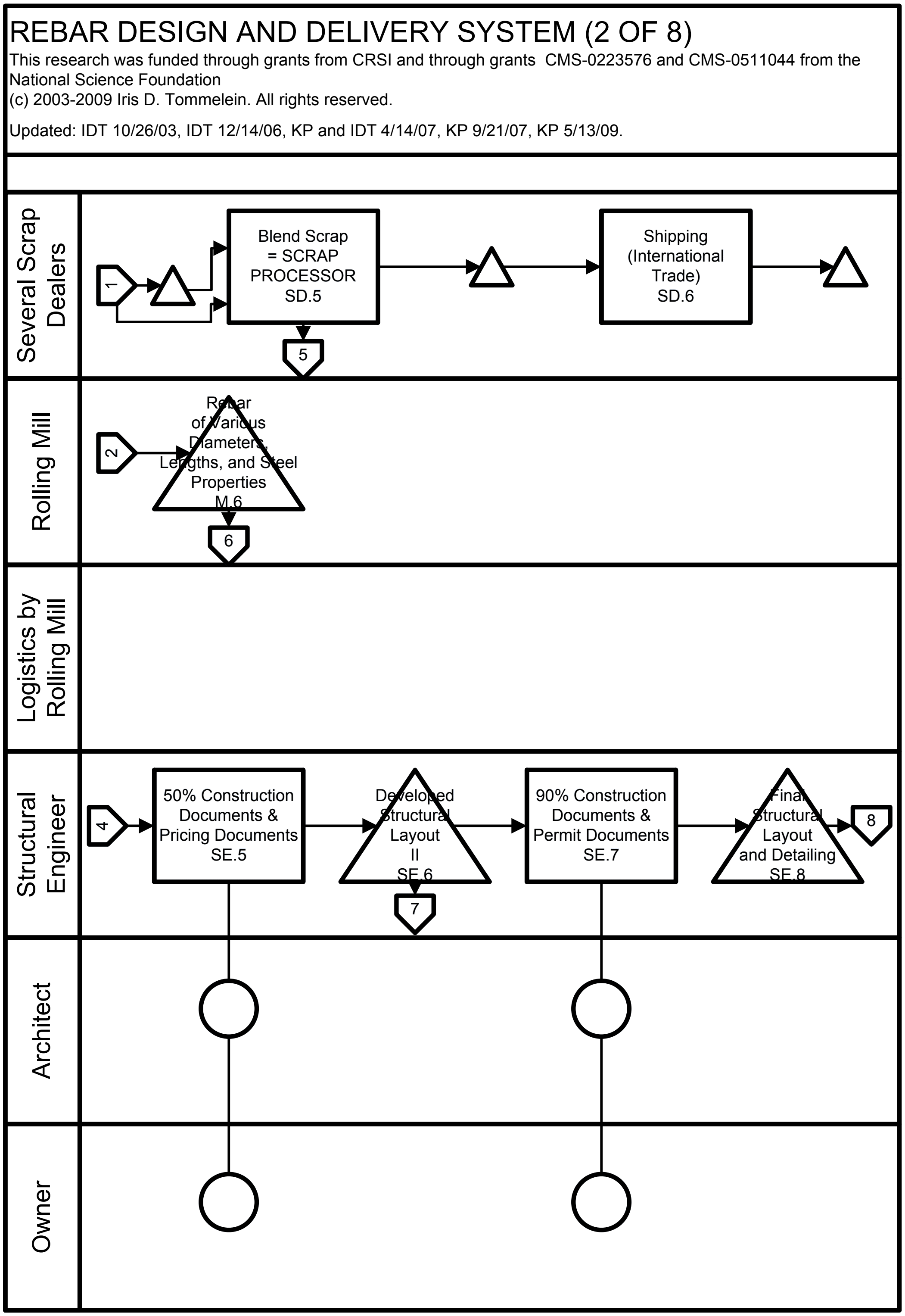

Figure A5 (2 of 8): Cross-functional diagram of the rebar design and delivery system

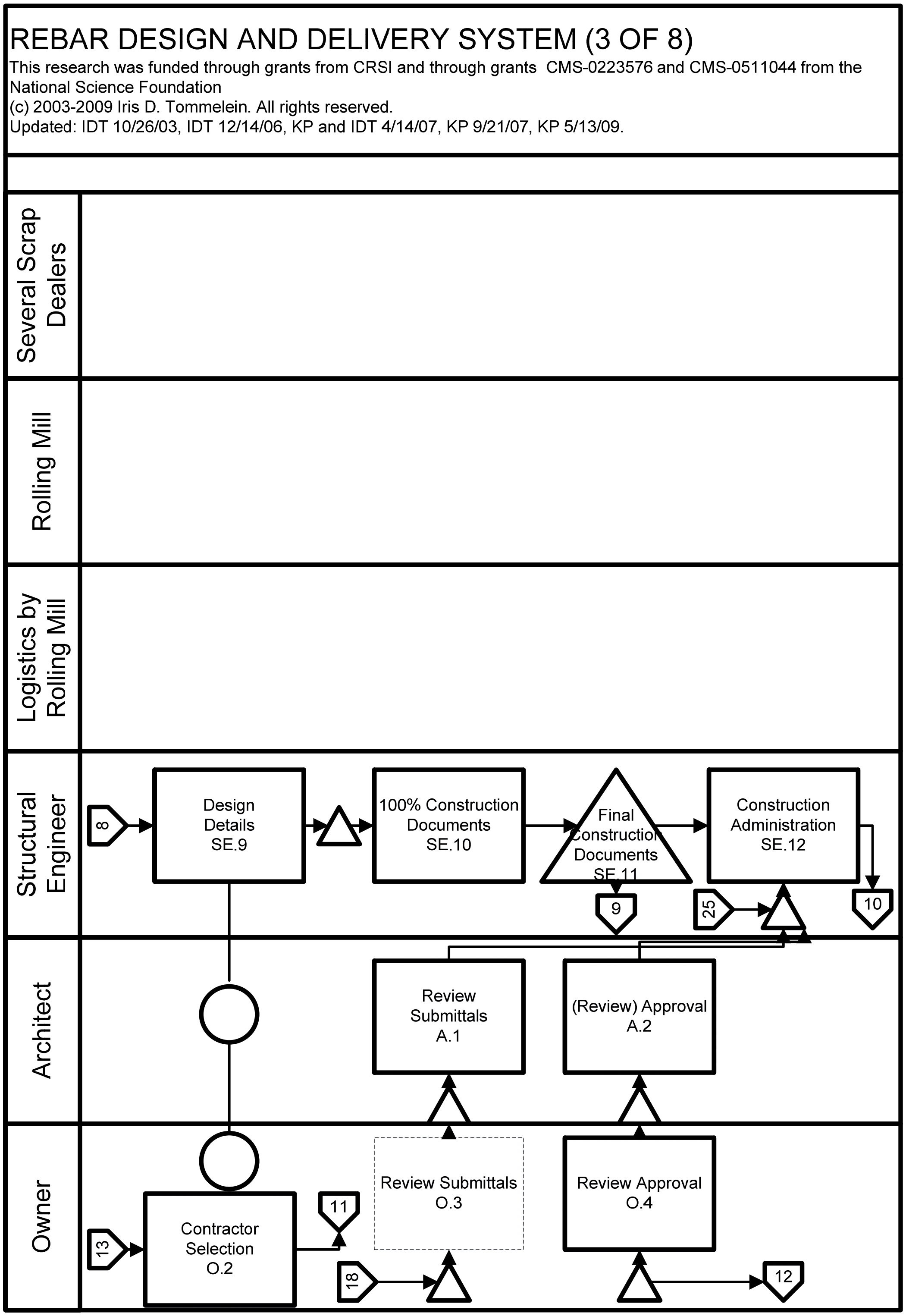

Figure A5 (3 of 8): Cross-functional diagram of the rebar design and delivery system

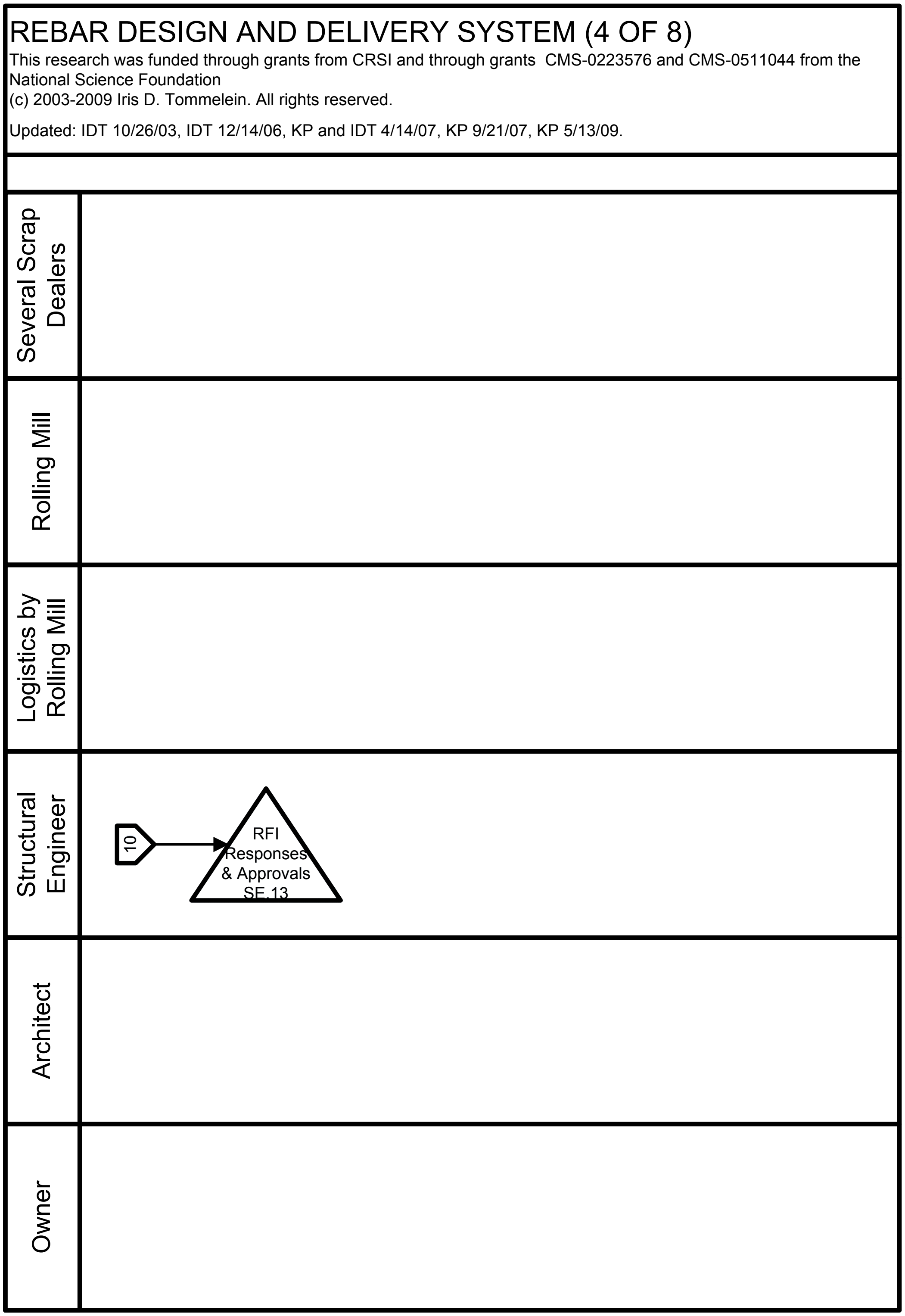

Figure A5 (4 of 8): Cross-functional diagram of the rebar design and delivery system

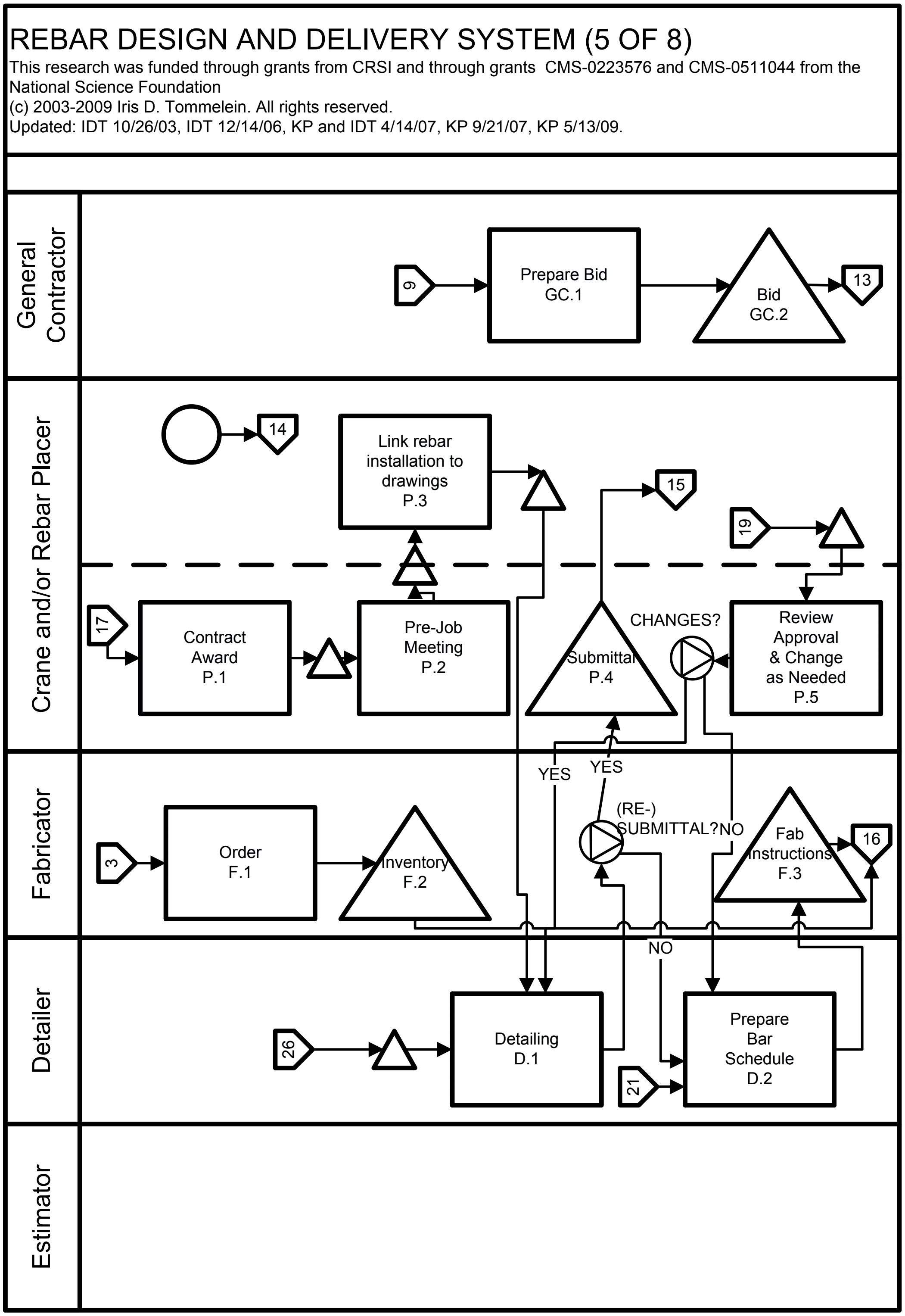

Figure A5 (5 of 8): Cross-functional diagram of the rebar design and delivery system

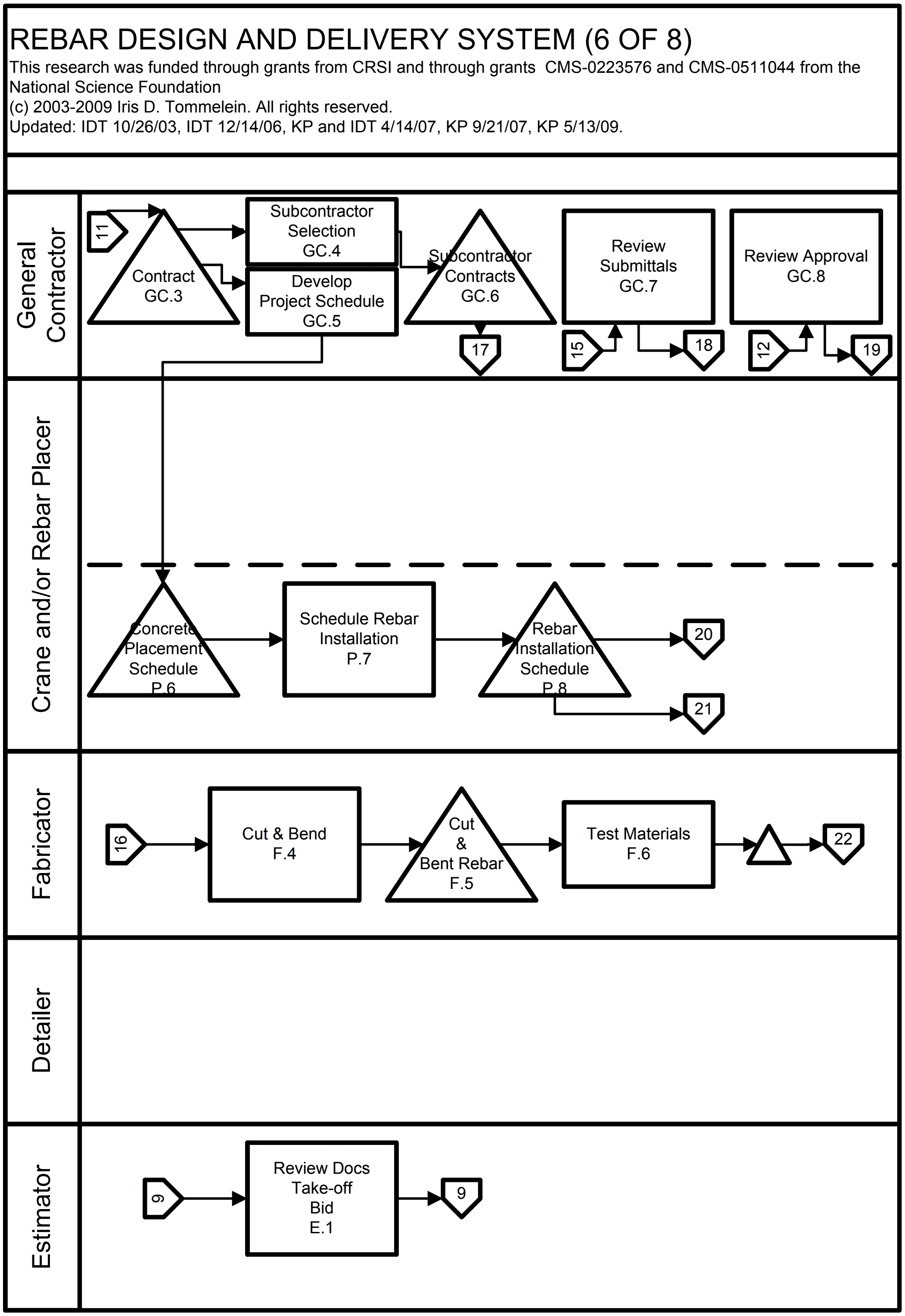

Figure A5 (6 of 8): Cross-functional diagram of the rebar design and delivery system

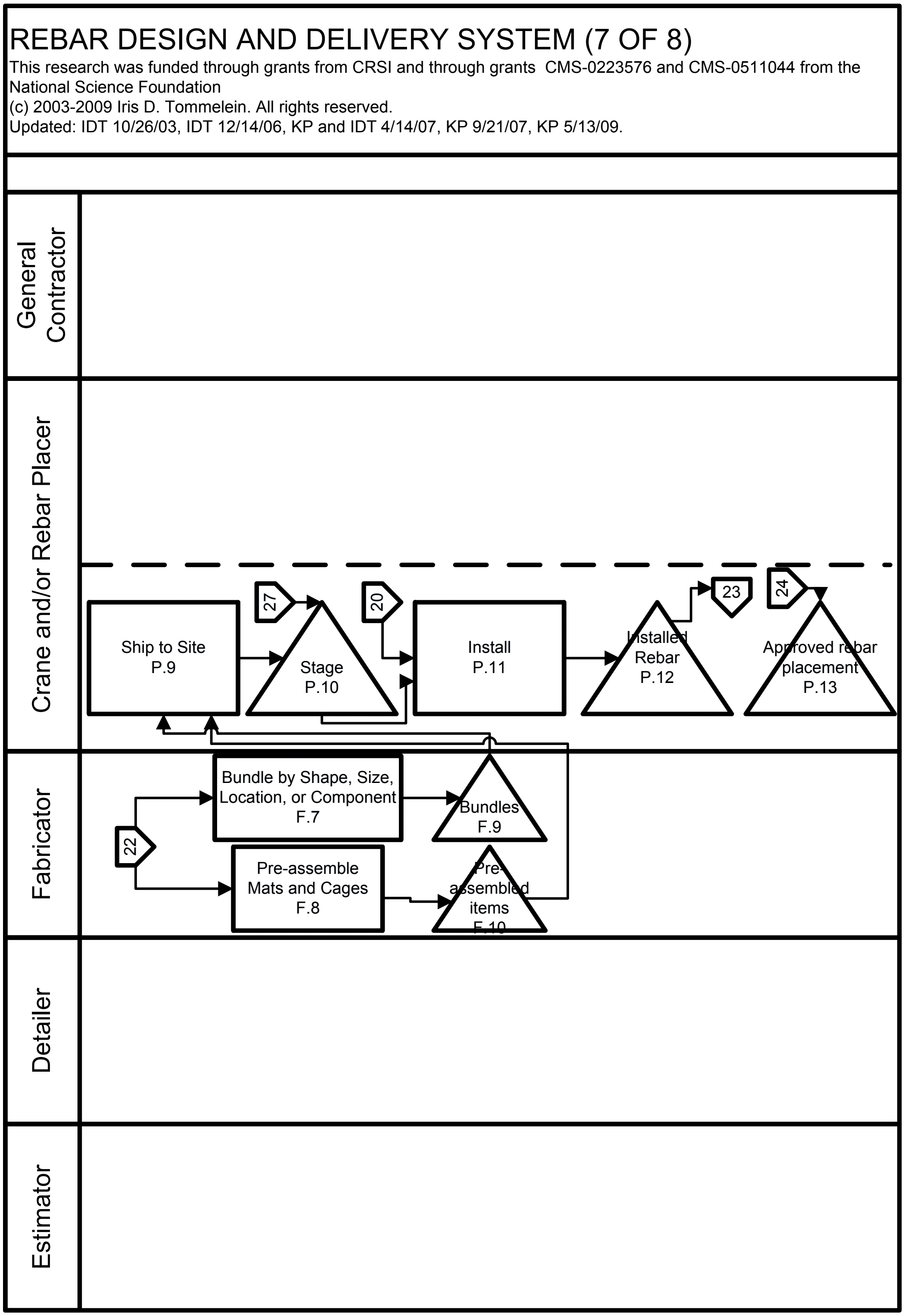

Figure A5 (7 of 8): Cross-functional diagram of the rebar design and delivery system

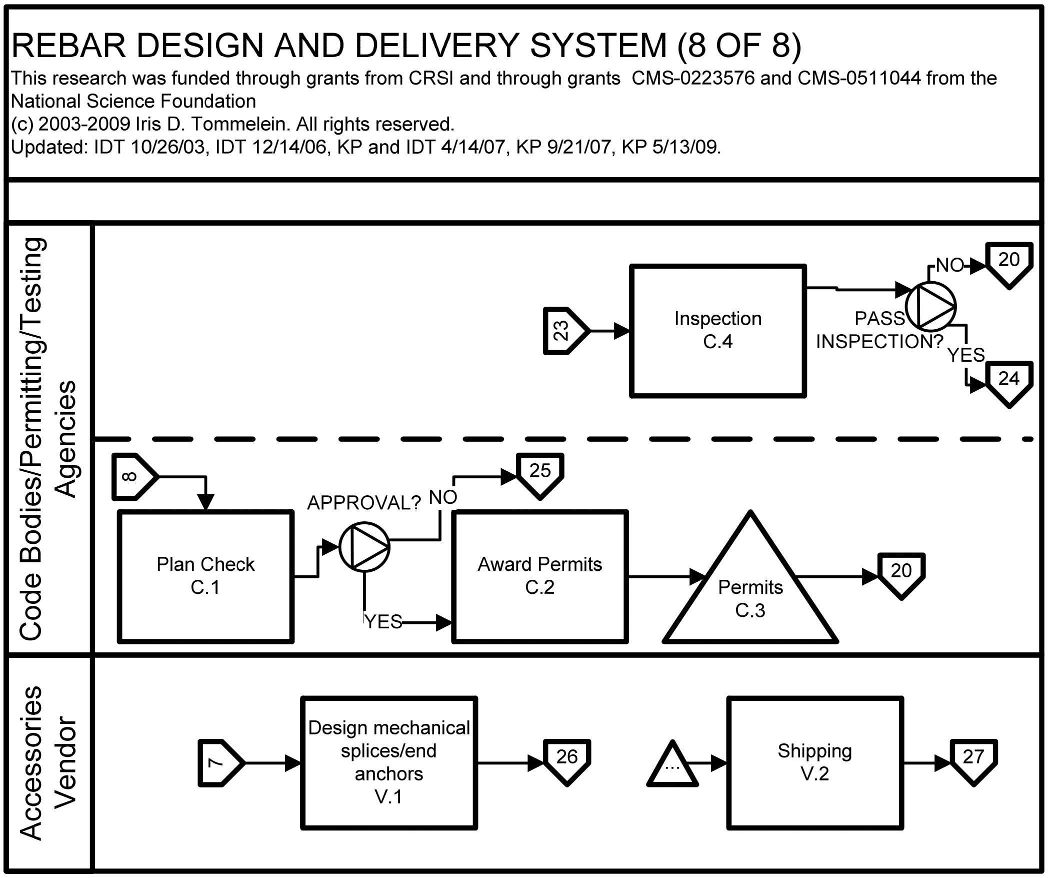

Figure A5 (8 of 8): Cross-functional diagram of the rebar design and delivery system

Figure A5 lists activities performed by each direct stakeholder. The following text describes these activities in detail.

A.4.2. SCRAP DEALERS (SD)

SD.1. **Scrap Source [Buffer]:** Rebar is made from all kinds of old steel (e.g., automobiles and soda cans), thus it is nearly 100% recycled material (Concrete Reinforcing Steel Institute 2007a). Metal scrap materials get processed in a mini mill (Tamco Steel Inc 2008; Wikipedia 2007).

SD.2. **Collect from Source & Store = SCRAP PEDDLER [Process]:** The scrap peddler buys materials at the source, then sorts and collects them for reselling.

SD.3. **Scrap by Type [Buffer]:** Sorting by type of material is necessary to help buyers with subsequent scrap blending.

SD.4. **Identify Market = SCRAP BROKER [Process]:** the scrap broker works with scrap peddlers to identify buyers for scrap materials and to set up sales and shipping agreements.

SD.5. **Blend Scrap = SCRAP PROCESSOR [Process]:** The scrap processor (which could be a mini mill) mixes ingredients in the quantities needed to achieve rebar performance requirements (strength, ductility, etc.) as specified, e.g., by ASTM (2008a; 2008b).

SD.6. **Shipping (International Trade) [Process]:** A significant amount of scrap is being exported (e.g., to China) for processing there. Steel ingots may then be shipped back to the US for rolling (International Iron and Steel Institute 2007).

A.4.3. ROLLING MILL (M)

M.1. **Scrap Mix [Buffer]:** The mill purchases scrap mix material and adds the balance of elements (e.g., vanadium, copper, and manganese) in order to obtain the chemistry needed to make rebar of the desired grade. The pricing of scrap material is the most volatile cost for the mini mill (Richenberger 2008).

Examples of steel grades used on the West Coast of the United States are ASTM A615 grade 60 and grade 75 (ASTM International 2008a) as well as A706 (ASTM International 2008b). ASTM A615 refers to carbon steel and ASTM A706 refers to low alloy steel (Concrete Reinforcing Steel Institute 2007b). The grade refers to the yield strength of steel: grade 60 steel must not yield under a loading of less than 60 ksi (kips per in^2), while grade 75 must not yield until it is loaded with more than 75 ksi. Grade 60 steel is the most commonly used and the least expensive grade of steel that mills make in the United States as of 2008. The industry has been increasing production of higher steel grades (grade 40 steel was still in use up until about 10 years ago, but no longer is readily available on the market today). As different scrap materials (with higher strength) and other elements are melted into the mix, the overall steel grade increases so that it can meet the test specifications of grade 75 steel.

Each grade of steel serves different applications. The American Concrete Institute (ACI) (2005) imposes restrictions on the strength of steel (steel grade) used in shear reinforcement in seismic zones, but for most purposes, either grade 60 or grade 75 steel is permissible. Grade 100 steel may also be used, though there are concerns from the structural engineering community about this steel being too brittle for seismic loading. A fabricator may substitute grade 60 steel with grade 75 steel on a project provided the structural engineer agrees to design for that strength.

An issue arises when mills roll so-called ‘multi-grade’ steel, i.e., steel that passes inspection and materials test(s) for both grade 60 and grade 75. Multi-grade steel reduces the complexity of handling rebar by fabricators and placers, as one bar can pass two inspections. However, structural engineers design elements with a given steel strength in mind, and use this strength to determine the minimum size of members. If an engineer is expecting one grade and another one is used, the structural member may perform differently than the structural engineer expects.

M.2. **Elements [Buffer]:** In addition to scrap materials, elements such as manganese, vanadium, and carbon are added to rebar steel mixes in order to achieve the characteristics of strength and behavior of the material, as mandated by the American Society for Testing and Materials (ASTM). Elements make up a small portion of the mix (on the order of 5% by weight), but they can have a large impact on the steel grade. For example, addition of vanadium increases the yield strength so that grade 75 steel yields at 80 ksi (grade 80 steel). Elements can also have a large impact on cost, as element pricing is volatile compared to other costs for the mini mill (Richenberger 2008).

M.3. **Mix Recipe & Melt [Process]:** Mixing and melting is an energy-intensive batch process. Mixing and melting happens in the 'melt shop,' consisting of a large furnace, a ladle, a caster, a tundish, and a billet mold. The furnace heats the scrap to 3100°F [1704°C]. Once the scrap is melted, other elements are added to achieve the desired chemistry for the rebar. The molten steel is ladled into casters and then poured into the tundish, which pours steel into billet molds. The tundish needs a continuous supply of molten steel, or steel will cool on it and impede the flow, requiring the melt shop to stop to clean the tundish before more billets can be molded. For this reason, the casters are paced to the furnace to ensure a continuous flow of molten steel through the tundish (i.e., the casters may not operate at their full capacity, but the furnace will operate at capacity). In the United States, when mini-mills are used for rolling rebar, a typical batch (or "heat") size is approximately 120 T [109 tonnes] (AIST 2008; DelRosario 2008). Figure A6 shows molten steel being poured from the tundish into the billet molds.

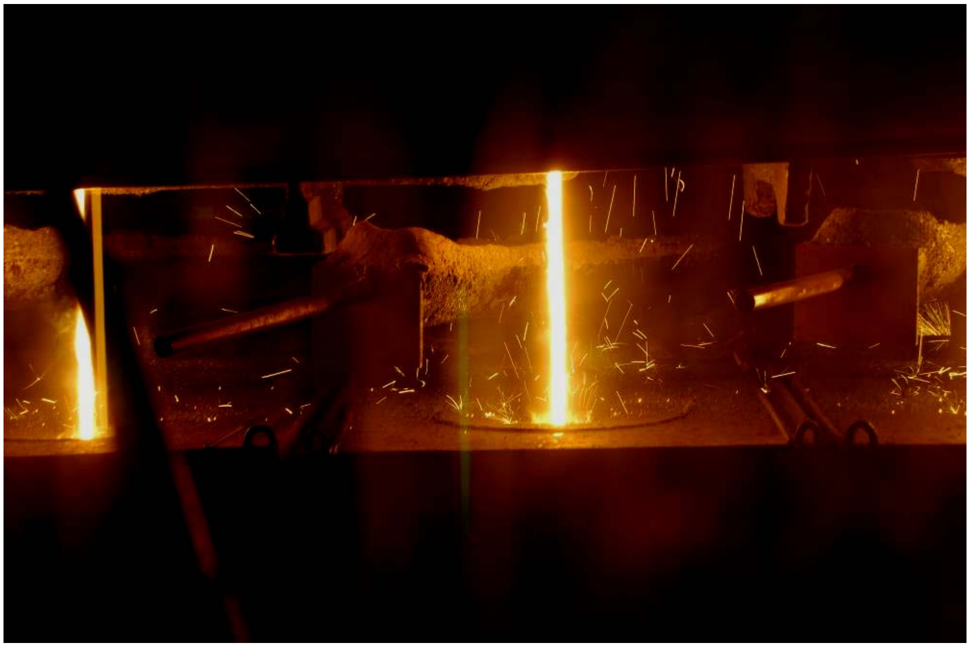

Figure A6. Molten steel is poured from the tundish into billet molds at Tamco Steel, Inc. (photograph taken by Iris Tommelein on 11/10/08)

M.4. **Billet [Buffer]:** Melted steel is shaped into billets, approximately 1 T pieces of steel with 5 in x 5 in cross sections (DelRosario 2008), that are cooled and stored. Table 1 lists typical billet lengths for given bar sizes, but mills can produce any length and will do so when a project warrants it (e.g., project needs a full heat of steel with a non-standard billet length). In production, the melt shop outpaces the roll mill, in part because of the setup time for the roll mill to roll a different bar size and in part because of the capacity of the re-heat furnace. Due to the mismatch in production rates between the melt shop and the roll mill, not all steel continuously flows through the mill. At one mill, about 60% of the billets are "hot charged," that is, rolled into rebar immediately after being shaped in the melt shop (DelRosario 2008). The melt shop can produce billets faster than the roll mill can roll bars, so about 40% of the billets from a given heat must be cooled and rolled later.

Table A1. Billet lengths according to bar size

Bar Size	Billet length (ft)
#4	20, 30, 40 , 60
#5	20, 30, 40 , 60
#6	20, 30, 40 , 60
#7	60, 70, 72
#8	60, 70, 72
#9	60, 70, 72
#10	60, 70, 72
#11	60, 70, 72
#14	60, 65, 72, 80
#18	60, 65, 72, 80

M.5. **Reheat (if needed) and Roll Bars [Process]:** Based on a production schedule for rebar of certain quantities and types, a billet is hot-charged or drawn from inventory, reheated, and made into rebar. Figure A7 shows a billet being reheated before it enters the Tamco Steel, Inc. roll mill to be shaped into a bar. “Reinforcing bars are milled by pouring molten steel into casters and then running it through a series of stands in the mill, which shape the steel into reinforcing bars.” (Concrete Reinforcing Steel Institute 2007a). Figure A8 shows molten steel being rolled into bars in the Tamco Steel, Inc. roll mill. “The cross hatchings, called ‘deformations,’ help concrete bond with the reinforcing bar” (Concrete Reinforcing Steel Institute 2007a). Figure A9 shows a deformation for Tamco Steel Inc., located in Rancho Cucamonga, California. Each mill uses a characteristic deformation pattern.

Figure A7. A cooled billet enters the reheat furnace at Tamco Steel, Inc. (photograph taken by Iris Tommelein on 11/7/08)

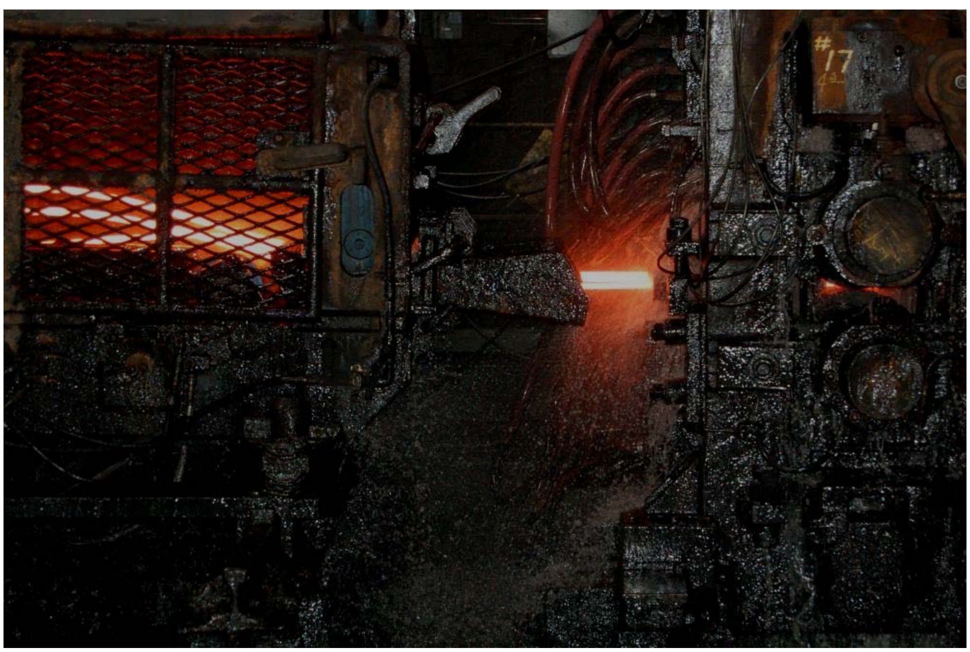

Figure A8. Molten steel is rolled into bars at Tamco Steel, Inc. (photograph taken by Iris Tommelein on 11/7/08)

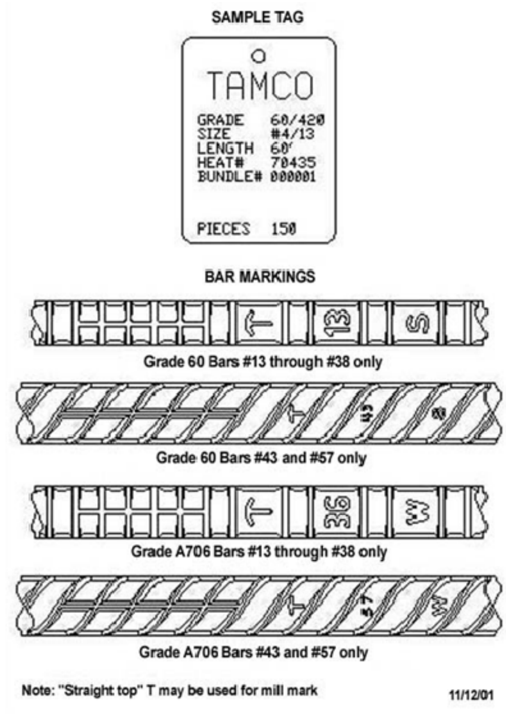

Figure A9. Sample bar tag and bar markings (Tamco Steel Inc. 2007a; 2007b)

Like melting steel, re-heating and rolling bars is an energy-intensive process. Accordingly, energy pricing impacts the decision to have the melt shop and roll mill start up and shut down, rather than run continuously at a fraction of capacity.

Bars of different material characteristics and geometry are made in batches for a selected period of time (hours or days), and then the mill switches over to making bars of other material characteristics and geometries. This production schedule, a so-called 'rolling' schedule, may be repeated at regular intervals, e.g., on approximately a 6-week basis. The rolling schedule is developed based on aggregate customer demand. However, as large orders come in, or customer demands shift, actual production schedule will vary from the rolling schedule. Furthermore, rolling schedules change gradually over longer periods of time as customer demands change. For instance, demand for #11 bar leveled off in late

2008, presumably reflecting the end of the high-rise construction boom in California (Richenberger 2008). Rolling schedules also may be adjusted to roll bars for big projects (projects requiring ~ 2,000 T of steel or more) (DelRosario 2008).

M.6. **Rebar of Various Diameters, Lengths, and Steel Properties [Buffer]:** The mill rolls rebar to standard lengths including 20 ft, 40 ft (most common), 60 ft, and 80 ft.

6.1. The mill is able to cut rebar to project-specific size. Having the mill do the cutting tends to be economical for the fabricator, especially for larger bar sizes, as their production process can be set up so that less material will have to be wasted and only needed materials are shipped. Furthermore, some fabricators may not have equipment readily available to cut especially larger bar sizes (#14 and up). For the mill to cut rebar to custom lengths, early and accurate project information needs to be relayed to them, and the order size must be large for them to offer this service economically, so it is not always possible to have non-standard lengths delivered (Richenberger 2008).

6.2. The mill ships directly to 'nearby' fabricators or ships to a warehouse depot to service a wider customer area. Typically, a mill will make shipments to any fabricators and/or warehouses within a day's drive.

A.4.4. LOGISTICS BY ROLLING MILL (L)

L.1. **Ship [Process]:** Shipping of rebar is done by rail or by truck. Trucking constrains the shipping length of rebar to 40 ft as this is a standard length for flatbed trucks using the highway system. Longer bars will require special trucking permits.

L.2. **Warehouse [Buffer]:** A warehouse may belong to a mill, a fabricator, or a third party. A third party warehouse is only used when rebar is not sold and shipped directly to a fabricator.

L.3. **Resell [Process]:** Mills sell directly to fabricators ~ 90 % of the time, but in some cases, they will sell material first to a warehouse for the rebar to be re-sold to smaller fabrication shops that do not have enough space to maintain inventory (Richenberger 2008).

A.4.5. STRUCTURAL ENGINEER (SE)

SE.1. **Schematic Design [Process]:** Initially, structural engineers will provide owners and architects with design options (called schematic designs) that are loosely, if at all, detailed. Schematic designs can be in the form of sketches, three-dimensional models, or even simple word descriptions. These designs are influenced by architectural constraints, such as window placement, and owner needs, such as performance requirements (i.e., the structure may have to remain operational during and immediately following a seismic event). Every functional element is identified and described. At the end of this design phase, design narratives describing design options may be given to a cost estimator (e.g., a cost consultant) for preliminary cost calculations which will accompany the design narrative when it is given to the owner. These cost estimates often have a lot of contingency at this phase, as there are only a few details, such as slab and shear wall thickness and a description of the foundations. If BIM and/or 3D modeling are being used on the project, it is incorporated at this phase.

SE.2. **Integrated Structural System [Buffer]:** Once the structural engineer has developed schematic designs, through conversation with the architect and (in)directly the owner, a structural layout is chosen that best meets the project requirements. Once a decision is made about the structural system, the SE meets with the architect to clarify the more relevant aspects of design: floor space, openings in concrete, bay lengths, etc.

SE.3. **Design Development [Process]:** Design development (DD) is where the structure literally begins to take shape. The DD process focuses on increasing the level of detail of the schematic designs. Once a basic structural scheme is decided upon, structural engineers work during DD on the overall system calculations (i.e. vertical loads, seismic demands, etc.). Major SE tasks in DD are (1) developing the subsystem interactions, (2) identifying all of the scope, (3) Developing typical details, (4) detailing the structure to provide enough information for global system interaction, (5) developing the major outline of concrete (basic dimensions, building footprint, column sizes, shear wall lengths and thicknesses) based on initial analysis, and (6) determining the basic rebar layouts (ignoring special cases or conditions at this point). At the end of this phase, cost estimates are again calculated, this time with reduced contingencies as more detail is now available. Also, in the case of more complex projects, outside peer review is often done on the DD documents. At this stage, the peer reviewer offers advice on how to build in future flexibility and identifies items in the design that may slow down the construction process.

SE.4. **Developed Structural Layout I [Buffer]:** After DD, a structural layout exists that can be used as a starting point for more detailed designs. This layout is coordinated with mechanical, electrical, and plumbing drawings, as well as with architectural drawings, to ensure no major collision issues exist (e.g., no ventilation ducts are running through the center of a structural member). Typical penetration details and integration in broad scope is covered.

SE.5. **50% Construction Documents and Pricing Documents [Process]:** The structural engineer details the structural elements to the point that a contractor can reasonably estimate the cost of constructing the structure. Not every piece of rebar must be shown at this stage, but congested members must be detailed enough to give the contractor and subcontractors an idea of what the construction cost will be. The SE details the most typical elements at interfaces at this stage to identify any atypical conditions, such as floor openings. The SE is also able to identify where coordination amongst trades is necessary. This set of drawings may or may not go out for costing, but a pricing package is developed at this stage. At this point, if the pricing package does go out, there will probably be one or two rounds of costing in this phase because more details are available to inform estimates.

SE.6. **Developed Structural Layout II [Buffer]:** The second structural layout is developed for a meeting with the architect to facilitate discussion about cost and coordination issues. This layout also specifically details any areas where clashes between trades exist, or conflicts between architectural and structural constraints.

SE.7. **90% construction Documents and permit Documents [Process]:** This set of documents serves as a "coordination print": it allows all of the major trades (mechanical, electrical, plumbing, and structural) to see if their respective systems are permissible given the planned structural layout. At this point, connection points between specialty items like canopies and awnings are designed and detailed. Architectural details are examined to see how these elements may affect structural stiffness. Finally, SEs will look at the effect on structural performance of anchoring, mechanical and/or medical equipment, casework, ceilings, soffits, and partial height walls.

SE.8. **Final Structural Layout and Detailing [Buffer]:** The final structural layout is used for clash detection. This clash detection is typically mandated by the architect to ensure everything is acceptable from a quality perspective. Site permits, block outs, openings, and embeds are reviewed based on this layout. This set of drawings is also submitted to permitting agencies for plan check. Figure A10 and Figure A11 show screen shots of a shear wall drawn in Tekla, a three-dimensional Building Information Modeling (BIM) software program. Three-dimensional representations make it easy for users to see how pieces will fit together onsite. This is useful for clash detection because clashes found in the model can be corrected before they become issues onsite. Figure A10 shows a two-dimensional view of the shear wall, and Figure A11 shows a three-dimensional view of the same section. Rebar congestion is more apparent in Figure A11, illustrating the benefits of three-dimensional views for clash detection.

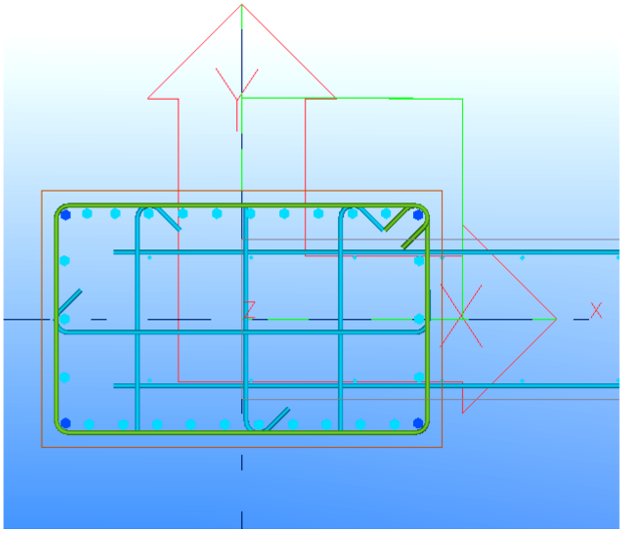

Figure A10: Two-dimensional view of a shear wall boundary element

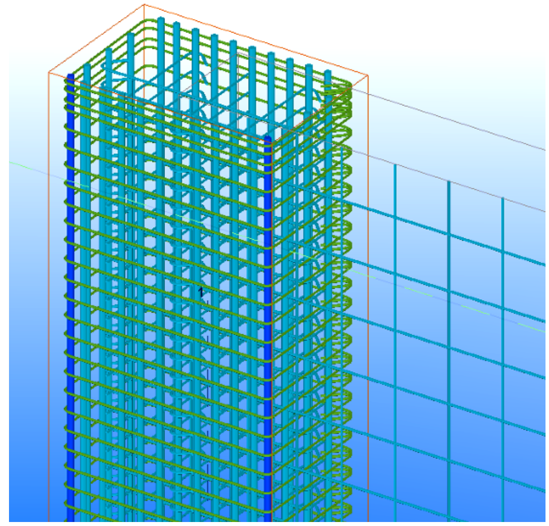

Figure A11: Three-dimensional view of the shear wall boundary element shown in Figure A10

SE.9. **Design Details [Process]:** In light of the coordination meeting held after the final structural layout is developed, final structural details are drawn.

SE.10. **100% Construction Documents [Process]:** All details and “how everything fits together” drawings are done. At this point, details that can cause problems in construction sequencing are addressed to attempt to preemptively deal with these before they cause schedule overruns on the project.

SE.11. **Final Construction Documents [Buffer]:** The final construction documents are often the set of drawings that are actually used for bidding. These drawings are ultimately the set used for construction.

SE.12. **Construction Administration [Process]:** Construction administration includes site visits, checking rebar and mix design from the relevant subcontractors, processing change orders and substitution requests, detecting contractor errors, resolving any product specification issues, monitoring concrete curing, and reviewing the shoring plan. This is not an exhaustive list of activities completed during construction administration, but it captures the major activities on most reinforced concrete projects. If the plan check reveals that there are issues with the plans, changes are made during the construction administration phase.

SE.13. **RFI Responses and Approvals [Buffer]:** The SE is responsible for reviewing RFIs (Requests for Information) and responding to these. The SE is also responsible for reviewing an architectural RFI response to ensure that structural integrity is maintained. As a part of the RFI process, the SE is responsible for delivering a set of As Built drawings to the owner along with Record Documents, which record any changes made to the original construction documents during the RFI and Change Order process.

A.4.6. ARCHITECT (A)

A.1. **Review Submittals [Process]:** The architect may review the plans for reinforcement submitted by the rebar subcontractor.

A.2. **(Review) Approval [Process]:** Request for Information (RFI) responses can originate in the architect's office or the structural engineer's office. In some cases, the architect will review the RFI and respond, and in other cases, the architect will view and approve the SE's response before it is acted upon by the contractor(s) and/or subcontractor(s).

A.4.7. OWNER (O)

O.1. **Owner Requirements for Building [Buffer]:** In order for an architect and structural engineer to design a building, each party needs input from the owner, e.g., architects and engineers need to know the functional needs the structure must fill. An owner's building requirements would contain details about the expected cost of the project, the expectations concerning size and general shape of the building, as well as specifications about the lifetime of a building and the expectations for safety in the event of a seismic, wind, or other hazard.

O.2. **Contractor Selection [Process]:** Ultimately, the owner decides, often with input from the architect or engineer, which general contractor (and in some cases, subcontractors) to hire. One notable exception to this is the case of public projects where law requires the low bidder be selected. Cost is usually thought to drive the decision of who to hire, but this decision is also influenced by past experience with the contractor, the contractor's safety record, and the contractor's experience in reinforced concrete construction.

O.3. **Review Submittals [Process]:** The owner is given the option of reviewing plans for concrete reinforcement submitted by the rebar subcontractor. This is not done in all cases, and even when given the opportunity, not all owners would exercise this right.

O.4. **Review Approval [Process]:** In some cases, the owner is responsible for responding to RFIs. These RFIs typically are concerned with user needs for space and their impact on construction sequencing.

A.4.8. GENERAL CONTRACTOR (GC)

GC.1. **Prepare Bid [Process]**: Once the SE completes the final construction documents, the documents are distributed to the general contractor, who distributes them to the rebar placer. The rebar placer then develops an estimate for the cost of the project's rebar work. The general contractor uses this information, along with information from other subcontractors, to prepare a bid price and bid package to submit for the entire project.

GC.2. **Bid [Buffer]:** A bid package, simply referred to as a 'bid,' consists of a description of the contractor's understanding of the scope of the work, along with a price and a schedule to complete that work.

GC.3. **Contract [Buffer]:** Upon the owner's selection of a general contractor, the general contractor is awarded the prime contract. This contract details the cost and payment schedule for the project, a schedule for the project, and addresses issues such as insurance, change orders, and safety precautions to be taken onsite. The contract will include a Notice to Proceed, specifying when work is to start.

GC.4. **Subcontractor Selection [Process]:** Once awarded the prime contract with the owner, the general contractor needs to award subcontracts. The final subcontractor selection process is based on the subcontractor's estimated costs, scope of work, and previous experience with the general contractor.

GC.5. **Develop Project Schedule [Process]:** The general contractor is responsible for generating a project schedule, detailing the order of work as well as the time each activity will take, jointly with input from the superintendent and subcontractors. The project schedule may be developed using commercially available software (e.g., Primavera Project Planner or Microsoft Project).

GC.6. **Subcontractor Contracts [Buffer]:** The general contractor develops a contract detailing the scope of work for the subcontractor to complete, the cost to complete that work, and the time in which the work is to be completed. The scope of work is a critical element in subcontractor contracts and therefore is subject to negotiation (Plue 2007).

GC.7. **Review Submittals [Process]:** The general contractor is the first to review any rebar placing drawings, RFIs, or change requests that are forwarded to the structural engineer, architect, and/or owner. In some cases, a general contractor may respond to an RFI and then have the response approved by the structural engineer, architect, and/or owner; in other cases, the general contractor will simply forward the RFI following the established protocol to reach the party that can authoritatively respond to it.

GC.8. **Review Approval [Process]:** The general contractor reviews the responses to drawings, RFIs, and change requests, updates the schedule if necessary, and then distributes information from the approvals to relevant subcontractors.

A.4.9. CRANE AND/OR REBAR PLACER (P)

P.1. **Contract Award [Buffer]:** The rebar placer is awarded the work based on bid price and package conditions. The placer is given notice of when work is expected to begin.

P.2. **Pre-Job Meeting [Process]:** The rebar placer attends a project pre-job meeting aimed at “getting everyone on the same page” before construction begins so the work will subsequently proceed smoothly.

P.3. **Link Rebar to Drawings [Process]:** After the pre-job meeting, the rebar placer knows more about the planned sequence of work and is thus able to make determinations about bars necessary to complete each phase of construction. This knowledge informs ordering of and the fabrication plan for rebar.

P.4. **Submittal [Buffer]:** The rebar placer submits details and placing drawings to the general contractor, architect, owner (possibly), and ultimately the structural engineer for approval (since the structural engineer serves as the engineer of record). The rebar placer may also submit RFIs in order to get clarification of the intent of the contract documents with respect to a particular detail or construction sequence.

P.5. **Review Approval & Change as Needed [Process]:** The structural engineer may approve the rebar placing drawings in their entirety, or accept only part of the placing drawings and require changes in some of the placing drawings. If change is necessary, the "Changes" rework cycle begins.

P.6. **Concrete Placement Schedule [Buffer]:** The general contractor prepares the overall project schedule (the master schedule). A part of that project schedule is the concrete placement schedule, used by the rebar placer to generate a rebar installation schedule.

P.7. **Schedule Rebar Installation [Process]:** The rebar placer uses the concrete installation schedule to determine what rebar needs to be placed by a given point in time. This rebar sequencing is known as the rebar installation schedule. Rebar placement on the critical path of a project will delay concrete placement activities and activities subsequent to concrete placement when not installed correctly and on time.

P.8. **Rebar Installation Schedule [Buffer]:** The rebar installation schedule documents when and how rebar will be installed on site.

P.9. **Ship to Site [Process]:** When rebar is received by the placers from the fabricators, it is shipped to the site to be placed. In some cases, the rebar is ready for immediate installation when it is shipped, while in other cases, onsite work is necessary before rebar can be placed (e.g., cages need to be assembled on the ground and flown into place).

P.10. **Stage [Buffer]:** Rebar may be stored in a given area on site, called the staging area. Some final fabrication steps may take place there as well, such as (minor) rebar bending, tying of cages, and other rebar preparation that could not be done off site (pre-fabricated). Alternatively, bars delivered to site may be offloaded from trucks and immediately placed (one-touch handling).

P.11. **Install [Process]:** Rebar is installed, from either the staging area or directly from the truck, according to the rebar installation schedule.

P.12. **Installed Rebar [Buffer]:** Rebar that is installed cannot be covered in concrete until the rebar placement has been inspected and approved.

P.13. **Approved Rebar Placement [Buffer]:** After an inspector approves the rebar placement (ensures that it meets all code and plan specifications), the rebar is ready to be covered in concrete.

A.4.10. FABRICATOR (F)

F.1. **Order [Process]:** The rebar fabricator places an order for rebar with either the warehouse or the mill directly, depending upon the size of the mill and the fabricator. Due to the volatility of the steel market price (California Department of Transportation 2007), many fabricators have opted to add significant inventory to their shop beginning in 2002. Building up inventory amplifies market volatility.

F.2. **Inventory [Buffer]:** The fabricator adds deliveries to in-shop inventory.

F.3. **Fab Instructions [Process]:** Fabrication instructions are based on information found in the bar schedule. They detail how many bars of each type need to be fabricated for a given job. Fabrication instructions include the bar sizes, number of bends, and possibly prefabrication orders for things like rebar mats and cages.

F.4. **Cut & Bend [Process]:** In the United States, nearly all rebar that requires fabrication is cut and bent using large machines in off-site fabrication shops, though some final cutting and bending may be necessary on site. A fabrication shop can run anywhere from eight (8) to twenty-four (24) hours each day, depending on how much work needs to be done. Figure A12 illustrates ties bent in the HarrisSalinas Rebar fabrication shop in Livermore, California.

Figure A12: Ties bent in the HarrisSalinas fabrication shop in Livermore, CA
(photograph taken by Kristen Parrish on 9/15/06)

F.5. **Cut & Bent Rebar [Buffer]:** Cut and bent pieces of rebar are tagged with the name of the fabricator, the name of the placer, and the name and location of the jobsite where they are going. Figure A13 shows one such tag.

Figure A13. Tagged rebar at the Oakland-San Francisco Bay Bridge site (photograph taken by Iris Tommelein on 4/26/07)

F.6. **Test Materials [Process]:** Increasingly, rebar needs to be tested at the fabrication shop to ensure that it meets the strength and ductility requirements set by ASTM. Testing is often required for road construction in California (Soulé 2006a).

F.7. **Bundle by Shape, Size, Location, or Component [Process]:** After steel has been tested and approved, it is either bundled for shipment or used to pre-assemble mats, cages, or other rebar shapes. Rebar may be grouped, or bundled, either by shape (e.g., bent or straight), size (e.g., # 4, # 5, etc.), location (e.g., where it needs to be installed onsite), or the component that it will be used for onsite (e.g., Column A-3).

F.8. **Pre-assemble Elements [Process]:** Once rebar is tested and approved, it can be used for pre-assembly. Pre-assembly involves making rebar mats, columns, walls, or cages in fabrication shops then shipping these assemblies to the site. Figure A14 shows a cage being pre-assembled in the Pacific Coast Steel fabrication shop in Fairfield, California. Pre-assembly is encouraged whenever possible because the production rate for this work is usually higher offsite than it is onsite, and the controlled shop environment tends to be a safer place to work than a construction site. However, pre-assembly is not always possible due to shipping constraints (i.e., pre-assembled elements may be too heavy to ship following certain routes) or site constraints (i.e., there is not room to move pre-assembled items into place onsite).

Figure A14. Rebar cage being pre-assembled at the Pacific Coast Steel fabrication shop in Fairfield, CA (photograph taken by Kristen Parrish on 12/1/06)

F.9. **Bundles [Buffer]:** Bundles of rebar are staged in the fabricator's shop until they are shipped to the site.

F.10. **Pre-Assembled Items [Buffer]:** Pre-assembled items are staged in the fabrication shop until they are ready to be shipped to the site for installation. Figure 15 shows pre-assembled shear wall boundary elements at CMC Fontana in Rancho Cucamonga, California waiting to be shipped to site.

Figure A15. Pre-assembled shear wall boundary element in the CMC Fontana Steel fabrication yard (photograph taken by Iris Tommelein on 11/7/08)

A.4.11. DETAILER (D)

D.1. **Detailing [Process]:** When a contract is awarded, a rebar detailer specifies the location and size of each piece of rebar to be placed in a project. This activity is known as detailing. Detailing a job can be easy or difficult, depending on the complexity of the design and the quality of the information provided. If structural drawings have a lot of information, detailing is easier than when drawings have little detail or 'typical details' that require modification. The detailer is responsible for generating placing drawings and therefore needs to have a sense of both the structural intent of each concrete element being detailed as well as the capabilities of the rebar placer(s).

D.2. **Prepare Bar Schedule [Process]:** Detailers generate lists of bars that need to be placed on a given project. This list of bars is known as a bar schedule. Bar schedules contain information about bar bends, bar sizes, bar lengths, and total bar tonnage.

A.4.12. ESTIMATOR (E)

E.1. **Review Docs Take-off Bid [Process]:** When the rebar placer receives the construction documents, they are given to the estimator. Estimates include labor and material costs. In the United State, many contractors calculate labor costs using Structural Activity Codes (SACs) that relate construction methods to productivity rates. The estimator completes a quantity takeoff and uses that to estimate the material cost of the work. Estimators may also adjust their estimate up or down to reflect accessory costs, site constraints, or previous experience with the contractor. The estimate is given to the rebar placer who reviews it before passing it on to a general contractor as a part of the rebar bid.

A.4.13. CODE BODIES/PERMITTING/TESTING AGENCIES (C)

C.1. **Plan Check [Process]:** After construction drawings are complete, city, county, state, and/or federal agencies—as required by law—must check the plans to ensure conformance with relevant structural codes and in some cases, architectural constraints (this is especially common when performing work on a historic landmark). If plans are approved, then permits are awarded. If plans are not approved, comments are returned to the structural engineer and/or architect so changes can be made.

C.2. **Award permits [Process]:** Permitting agencies can be city, county, state, or federal agents. Permits must be secured prior to the start of certain types of work.

Specific to reinforced concrete construction, permits often need to be obtained to begin excavation and site work, as well as to begin any concrete pours.

C.3. **Permits [Buffer]:** Permits awarded by the permitting agency are required to be onsite before work can begin. The permits are to remain onsite throughout the project.

C.4. **Inspection [Process]:** A representative from a (private) agency, known as an inspector, must approve rebar placement before any concrete can be placed. This process can be tedious, as most codes are not entirely explicit. Thus, the structural engineer's interpretation of a code may be different from an inspector's interpretation of the same. The rebar placer, structural engineer, and inspector must work together to determine an acceptable rebar configuration so construction can proceed. Once rebar placement is approved, concrete placement can proceed. If rebar placement is not approved, the rebar placer and the inspector have to reach an agreement about what needs to be changed for the rebar installation to be approved and allow concrete placement to commence. In extreme cases, this may mean that bars are removed and then placed again in a different configuration.

A.4.14. ACCESSORIES VENDORS (V)

V.1. **Design Mechanical Splices/End Anchors [Process]:** In some elements of a structure, rebar is extremely dense. In these situations, it is often impossible to use lap splices or hooked ends for rebar. Instead, mechanical splices and end anchors are used. These devices reduce rebar congestion, but still meet code requirements for strength of rebar and confinement of concrete, respectively.

V.2. **Shipping [Process]:** Once it is determined which mechanical splices and/or end anchors are necessary for a project, these items are shipped to the site and used during rebar installation.

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