EXPLORATION OF SET-BASED DESIGN FOR REINFORCED CONCRETE STRUCTURES

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ABSTRACT

To explore the feasibility of improving the delivery process of reinforced concrete, we focus in this paper on reinforcing bars (rebar) used in cast-in-place (CIP) concrete. Specifically, we describe the methodology for set-based design of rebar that we are pursuing in an ongoing research effort. Set-based design makes it possible to maintain feasible solutions for longer in the design process than is otherwise affordable using point-based design. It thereby allows for input from several project participants at the same time and early on, as well as throughout project delivery. Set-based communication helps participants avoid rework and through teamwork develop a more globally satisfactory design solution than would otherwise be the case. To illustrate the methodology, we examine the canonical example of reinforcement at a beam-column joint and study the relationships between those who design the joint and those who fabricate and install it: mainly the structural engineer, the fabricator, and the rebar placer. The set-based approach for concrete design is promising. It warrants further effort in characterizing sets at different levels of abstraction and in articulating what different participants value, both of which are needed for sets to be narrowed effectively and for the process to lead to a solution.

KEY WORDS

lean construction, product modelling, set-based design, reinforced concrete, rebar, design methodology, product development, design management, production system design

INTRODUCTION

Reinforced concrete is used in capital facilities in all sectors of the construction industry. Specialists involved in its supply chain include owners, architects, structural engineers, steel mills, concrete suppliers, reinforcing bar fabricators, placement contractors, craft labourers, general contractors, formwork contractors, and others. That they are numerous reflects the advanced technological understanding and capabilities that we exploit today to build structures to meet increasingly stringent owner and societal requirements. The need to specialize, however, has gone hand-in-hand with fragmentation of the industry

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resulting in a sub optimal project delivery process. Metrics of performance leave no doubt that current practice can be improved significantly (Tommelein and Ballard 2005): there are many unnecessary iterations and large amounts of rework in design and detailing, numerous requests for information from the builder to the designer, long lead times to fabricate and deliver rebar, time consuming and costly constructability problems discovered during on-site placement, tons of paperwork cluttering the process, and huge legal issues challenging many a project.

To globally improve project delivery, participants from across the supply chain must collaborate starting at the project outset to exploit the unique process- and product design and execution capabilities of individual members of the team as well as synergistic and collaborative relationships that may be developed within the team. Furthermore, early collaboration may be supported using set-based design, a methodology that encourages all participants to engage in exploring the entire design space and to narrow that space collectively until a globally satisfactory design is found. The concept of set-based design and its applicability in reinforced concrete design is presented in this paper via an example of rebar used in a concrete beam-column joint.

STRUCTURAL ENGINEERING DESIGN PRACTICE

POINT-BASED DESIGN

A point-based design methodology (Figure 1) is often followed by structural engineers. Point-based design involves selecting a single structurally-feasible design option 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. The first design thus selected by a structural engineer tends to be uninformed by the expertise of rebar fabricators, placers, and concrete suppliers who will perform the actual rebar detailing, rebar placement, and concrete placement. Not including such expertise may produce a design that meets structural performance- and contractual requirements (e.g., building permitting), yet that is suboptimal from a more general project perspective. This is not to imply that the structural engineer is not concerned with constructability. Rather, a locally-optimal design is a by-product of the structural engineer being hired to develop one point solution. Structural engineers design for constructability to the extent that they are able. However, rebar fabricator capabilities are not necessarily considered. Likewise, contractors may offer their expertise, but the time and contract structure used in many projects does not allow for this conversation to significantly impact the initial design. Clearly, there is room for improvement in the practice of design.

SET-BASED DESIGN

In contrast to point-based design, set-based design focuses on keeping the design space as open as possible for as long as possible. The design space is articulated differently in different companies and domains, depending on use. For instance, in automobile manufacturing, Toyota spends a lot of time upfront doing experimentation to fully explore the design space (Ward et al. 1995). In structural engineering, a design space may comprise sets of design options that can be continuous or enumerated as discrete design options depending on the level of abstraction. Specific designs are not considered alone; rather, the *set* of options that remain in the design space are considered feasible. Instead of specifying a design before all the constraints are known, design decisions are postponed until the “last responsible moment”. Ballard (2000) defines the last responsible moment as the “point at which failing to make the decision eliminates an alternative.”

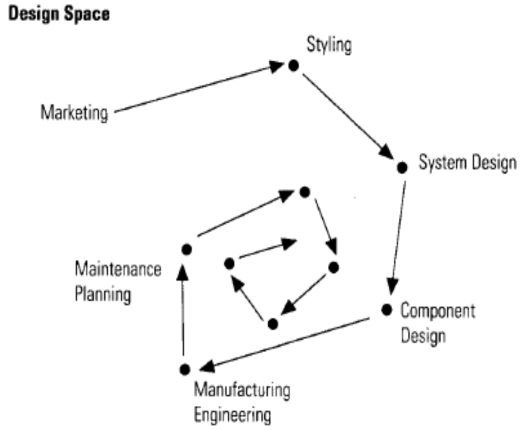

Figure 1. Point-Based Engineering Process (Ward et al. 1995)

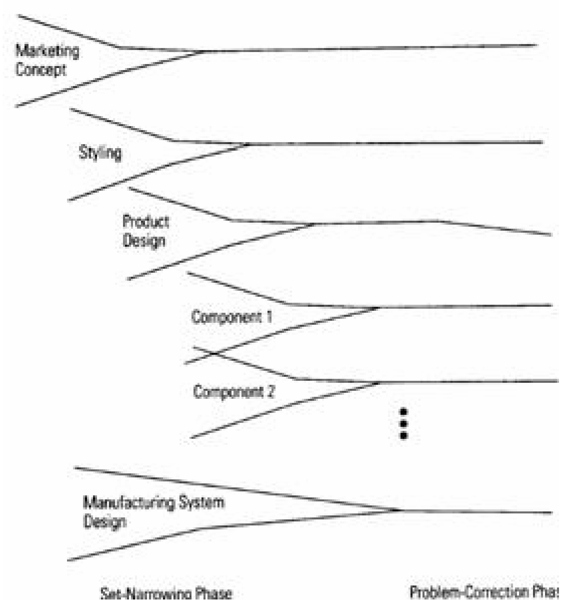

Figure 2. Set-Based Engineering Process (Ward et al. 1995)

Set-based design may be viewed as a funnelling process (Figure 2). At the start, there are many design options. As constraints are invoked, the number of designs still feasible gets reduced (Sobek et al. 1999). In order to implement set-based design, there must be a work structuring effort as the project unfolds to determine who the stakeholders are. Relevant stakeholders will likely be different at various phases of the project. Their input is needed to assess the quality and feasibility of subsets of the design space. A key to the success of set-based design is knowledge sharing; whenever the feasible design space is reduced, the reason for eliminating any part of it needs to be documented and made accessible to all relevant stakeholders. Preserving the maximum number of feasible designs as long as possible reduces the likelihood that rework will be necessary and allows all project participants to leverage their unique, individual, and team-based expertise to make the project successful.

RELATED WORK ON SET-BASED DESIGN

Many references to set-based design deal with the concept of set-based concurrent engineering as described by Ward et al. (1995). Set-based concurrent engineering focuses on “delaying decisions, communicating ‘ambiguously’, and pursuing excessive numbers of prototypes”. “Concurrent” refers to involvement of many disciplines at the same time. At Toyota, set-based design is a process in which “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). In contrast to concurrent engineering, set-based design may or may not stay within a single discipline. It focuses on exploring many options (the design space) but does not require that many prototypes are developed or tested.

Set-based design is viewed as a key ingredient of Toyota's economic success. Toyota examines many designs at the project outset and continually tests these designs to ensure that all designs considered are robust; that is, each design is to be successful in a variety of environments. When the designers are confident that a sufficient number of robust design options have been explored, they begin to narrow sets. Toyota's company culture requires that when sets begin to be narrowed, no new designs will be considered. That is, when a set begins to be narrowed, it is "locked", it can no longer be expanded (i.e., backtracking is avoided). Likewise, Toyota's suppliers also practice set-based design (Liker et al. 1996). In order to preserve this narrowing-only approach, knowledge that allowed a set to be narrowed is captured in a "lessons learned" book. This book is available as a reference to any employee who needs/wants to review a given design and it captures organizational learning for use in other design efforts.

Sobek et al. (1999) fleshed out the principles describing set-based concurrent engineering as practiced at Toyota. The authors adapted these principles and use them as the working definition of set-based design in this paper. Three principles govern set-based concurrent engineering: (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 that determination is made, sets of acceptable design alternatives are developed and communicated to all involved participants. The second principle focuses on narrowing the sets. This is done by first determining what sets of design alternatives intersect which results in the set of potential final designs and second by imposing constraints and making selections based on criteria such as robustness. In order to reduce the sets of feasible options to a final design, the sets are gradually narrowed while detail on the designs increase. Care is taken to ensure that discussions and designs stay within the previously accepted feasible options. Finally, the third principle focuses on narrowing the set down to a single point, representing the final design that will be manufactured.

Set-based design has been studied for its applicability in the field of software design, especially for parametric design software (e.g., Nahm and Ishikawa 2006). Lottaz et al. (1999) showed how set-based design applies to structural and HVAC system design. Castro-Lacouture and Skibniewski (2006) studied parametric set-based design in civil engineering, applied to the rebar industry. Others (e.g., Ulrich and Eppinger 2004, Ford and Sobek 2005) explored set-based design principles in production development. The tenets of set-based design have also been discussed in, e.g., Finger and Dixon (1989a and 1989b), Aganovic et al. (2004), and Stephenson and Callandar (1974).

SET-BASED DESIGN METHODOLOGY

Figures 1 and 2 illustrate, respectively, the point-based and the set-based design methodologies. The point-based design process requires backtracking or iteration; the need for these is reduced and possibly eliminated altogether in the set-based design process. Set-based design presents a unique opportunity for collaboration of project participants across the supply chain. For set-based design to be efficient, the relevant stakeholders should be involved in the decision making process. An initial work structuring effort is therefore needed to determine who is to have a say and who is impacted by what decisions. These participants (stakeholders) are to collaborate in order to both develop and subsequently narrow the design space while ensuring that (1) all options are considered and (2) the globally most satisfying solution gets selected. Set-based design aims to reduce the rework inherent to the point-based design methodology while simultaneously adding value to the project by making it possible for participants to postpone commitment and considering many design options.

An intuitive example helps to contrast point-based with set-based design (Ward et al. 1995). Consider scheduling a meeting. Using a point-based process for scheduling, the scheduler might send out an announcement that a meeting is necessary and propose to schedule it at a time suitable to him/her, e.g., for 10 am on Monday morning. As the meeting attendees read the announcement, schedule conflicts will likely be revealed, causing back-and-forth communication and causing the meeting time to shift many times until a meeting time is reached that is agreeable to many if not all. In contrast, using a set-based process for scheduling, the scheduler could announce that a meeting is necessary and send out all his/her available time and times currently booked but that might be rescheduled. Then, each of the meeting attendees could compare their own availability with that of others and negotiate which meetings are best rescheduled until a meeting time manifests itself out of the attendees' constraints. The set-based process eliminates unnecessary back-and-forth communication and expedites the meeting time selection.

EXAMPLE OF SET-BASED DESIGN FOR REBAR

The canonical example of reinforcing a concrete beam-column joint in a reinforced concrete frame (Figure 3) illustrates set-based design in a structural engineering environment. The example walks the reader, step by step, through the set-based design process used to design the reinforcement for the beam, the reinforcement for the column, and finally to arrive at a beam-column joint design. Before set-based design can begin, it must be determined which project participants are relevant stakeholders to the beam-column reinforcement decision. In this case, these stakeholders are determined to be the general contractor and labourers who will be responsible for concrete placement, the

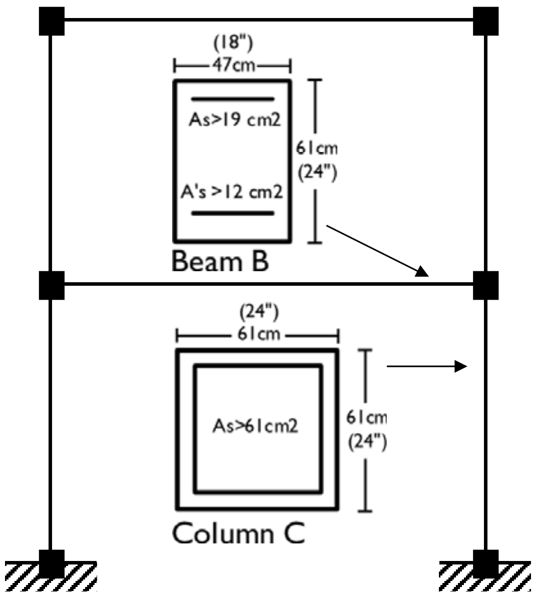

Figure 3. Canonical Example of Reinforced Concrete Frame with Beam B and Column C

rebar fabricator, who will be responsible for detailing the section, and the rebar placer, who will need to place the bars as specified in the fabricator's drawings (in some cases, the rebar fabricator and rebar placer are the same).

STEPS OF SET-BASED DESIGN

Step One: Map Design Spaces

To begin, the structural designer along with the stakeholders as listed determine the possible sets that define the design spaces. In the case of the reinforced concrete frame example, there are two sets of design spaces overall: one for the beam and one for the column. To map the feasible design space for the beam, the designer must calculate the minimum area of required reinforcement, e.g., 19 cm^2 (3 sq. in.) for the top steel and 12 cm^2 (1.8 sq. in.) for the bottom steel, based on the ACI-318 structural concrete code (American Concrete Institute 2005). This gives the minimum areas of tension steel, A_s, and compression steel, A_s', that are necessary to achieve the required beam flexural strength. In this example, the beam is 47 cm by 61 cm (18 in. by 24 in.), which requires A_s > 19 cm^2 (3 sq. in.) and A_s' > 12 cm^2 (1.8 sq. in.). Similarly, the minimum required steel area for the column is determined to be A_s > 61 cm^2 (9.5 sq. in.). ACI-318 further limits the steel reinforcement ratio (a ratio of steel area to concrete area for a given cross section) to a maximum of 0.025 in order to achieve ductile section behaviour.

Once these initial requirements (upper and lower bounds on the area of rebar) are determined, the question arises as to how to define the sets of options so that funnelling towards the final design can begin. In general, set-based design postpones narrowing the design space since it is best to keep as many design options open as long as possible. The set of possible designs is large in this case as there are many reinforcement configurations that would meet the steel area requirement. A computer could generate a set of design options that completely defines the feasible design space. However, later on in the design process, the rebar fabricator will need to generate placing drawings and thus spell out specific section details. Figure 4 shows a representative sampling of the beam design space, including beams representing various bar sizes, as well as various configurations (i.e., one or two layers of tension reinforcement). However, for brevity, our example does not show every possible reinforcement scheme. Likewise, Figure 5 shows different bar sizes as column reinforcement options in the column design space,

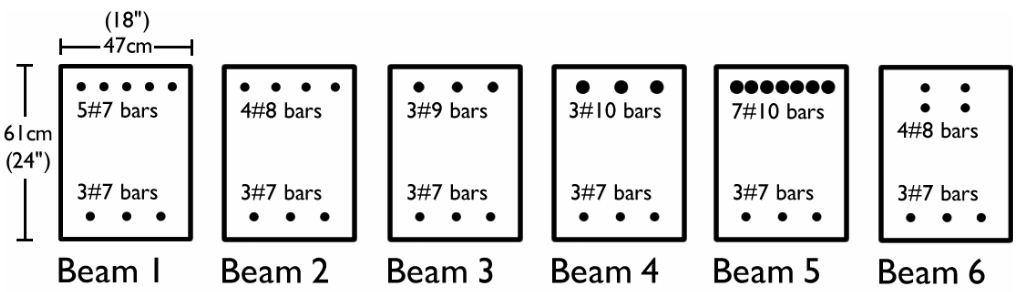

Figure 4. Sampling of the Design Space for Beam B

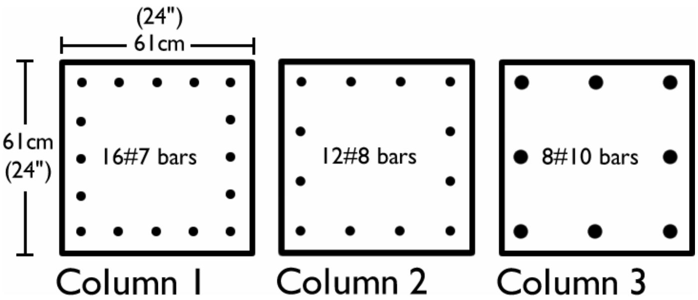

Figure 5. Sampling of the Design Space for Column C

Step Two: Find Compatible Combinations

After the design spaces have been mapped, the relevant stakeholders express their wants and wishes to find compatible combinations of design options. Constraints are imposed at this point in the design process (Figure 6). Both hard constraints, like code requirements, and soft constraints, like designer preference, are invoked to narrow the design space. Note that there is a focus on *narrowing* the set, so project participants must be cautious and work within the design space previously agreed upon rather than start dreaming up new solutions once the compatible combinations phase of set-based design is reached.

Both hard constraints and soft constraints help to narrow the design space. In the example, hard constraints are shown in black and soft constraints are shown in gray using the “no” sign used in traffic regulation. The hard constraints applied in this example are (1) joint depth requirements, $h_{col} / d_{b,beam} > 20$, and (2) the spacing requirements of the ACI-318. ACI-318 spells out these constraints to ensure that a given concrete mix (with given aggregate sizes) can flow between rebar upon placement. In reality, the concrete mix is itself a set with its own design space. However, for this example, we assume the concrete mix to be a given. Likewise, the example implies that the elements’ dimensions are a given whereas in reality they too can be characterized by means of a design space. The soft constraint applied is based on a “rule of thumb” in the structural design community, that it is preferable to have all of the reinforcement in one layer of bars if possible. This is because a member’s flexural capacity is greater when the steel moment arm is greater. A single layer of steel furthest away from the section centroid maximizes the moment arm of the steel. The same area of steel distributed over two layers would have a smaller moment arm and smaller flexural capacity. In addition, placement of a single layer of bars is typically easier than a double layer.

In Figure 6, all beams and columns that are feasible design options are denoted with a check mark. However, Beam 3, Beam 6, and Column 2 are feasible, but not preferred. Beam 6 is not preferred since it has two layers of reinforcement. Beam 3 and Column 2 might be less preferred even though smaller, more closely spaced bars create a more homogenous section, which results in superior material performance, since the number of bars drives the placement productivity down and raises constructability concerns (less space for concrete to flow through). This example illustrates the need for a “lessons learned” book. On one hand, if there is evidence that using Beam 3, Beam 6, or Column 2 creates a more globally satisfactory situation, then any of these elements can still be used. On the other hand, if these options are not necessary for more satisfactory project delivery, they should be eliminated from the design space.

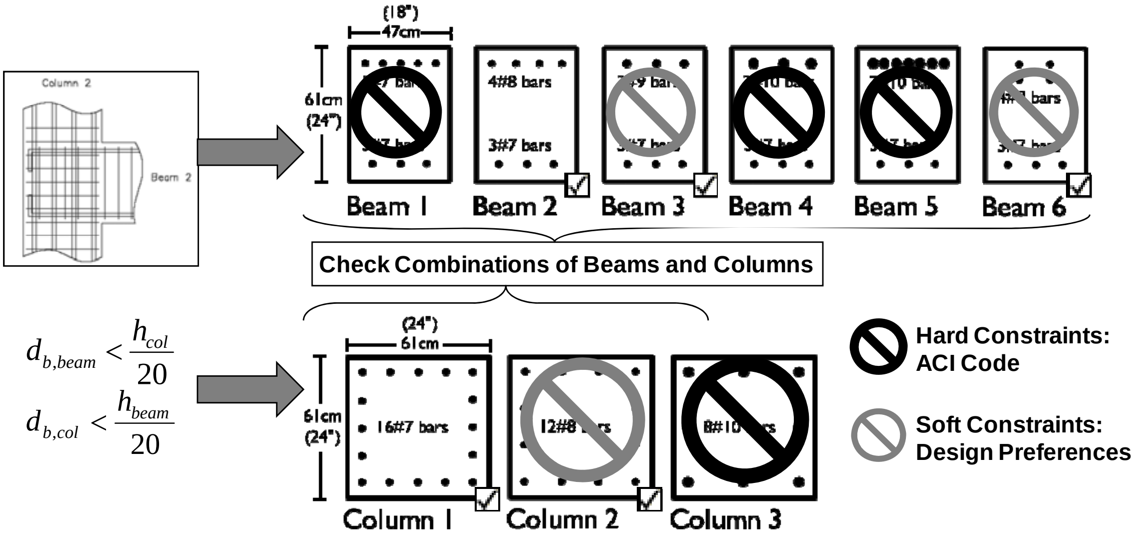

Figure 6. Compatible Combinations of Beams and Columns

Step Three: Make Commitment

Once there is a narrowed set of design options, as in Figure 6, a commitment to a final design can be made. This final design is arrived at through a natural funnelling of the design space, rather than simply selecting an arbitrary design and then re-working it as necessary until a constructible final design is reached. In our example, the set was narrowed until there was only one option remaining. It will not always be the case that only one design choice remains. However, by involving all relevant project participants, it is possible to select a final design that is more satisfactory in the global sense. If no solution exists given the hard and soft constraints, then a larger initial design set needs to be explored, or constraints might need to be renegotiated.

Figure 7 shows the design selected for Beam B and the design selected for Column C. By implementing set-based design, there was no need for negative iteration, or rework, to determine a final design. Furthermore, by involving all the project participants, including the builders, in Step Two, we ensured that the design that was eventually selected would be constructible.

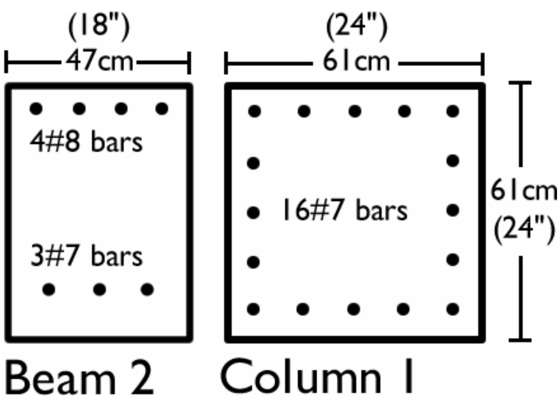

Figure 7. Final Design of Beam B and Column C

CONCLUSIONS AND FUTURE WORK

The example presented in this paper simply illustrates the concept of developing a set of design options (beam design option set), rather than a single design solution, and carrying it through along with other sets of design options (column design option set). The set-based approach for concrete design is promising. It warrants further effort in characterizing sets at different levels of abstraction and in articulating what different participants value, both of which are needed for sets to be narrowed effectively and for the process to lead to a solution.

The authors are working to define the appropriate decision unit for use in set-based design. The decision unit is the substructure that can be used as a means for making a design decision. In this example, the decision unit was a beam-column joint. It is likely that decision units will vary as a design progresses. At first, a decision unit could be an entire structure, and the decision is the type of construction (i.e., flat plate, moment frame, special moment frame, etc.). As the project progresses, decision units may become smaller as the design options are funnelled into a final design.

The authors are also working with a group of industry participants to develop a protocol for use of set-based design in a real-world setting. Thus far, the participants have expressed that in order for set-based design to be a feasible design methodology, a language needs to be developed that allows different stakeholders to communicate what is and is not feasible for their particular specialty. We are eliciting this language by presenting them with examples and soliciting their critical review and comments. When this language is developed, the project stakeholders will be able to more meaningfully discuss the possible intersection of their respective sets, and thus be able to choose designs that are more globally satisfactory.

Set-based design provides an opportunity for project participants to collaborate on structural design decisions early on- and throughout a project in order to generate value, while reducing rework and iteration found on too many capital projects today. The example showed how set-based design is efficient for capturing the needs of multiple project participants across the supply chain. This capturing may require more work on the front end of the project for more project participants, but it promises overall savings later on in project delivery.

In a hard bid scenario, set-based design may be difficult to implement as it requires the expertise of multiple project participants who are not typically determined at the outset of the project. Many contracts today further require that the structural engineer develop only a single design; to have them do otherwise may require a different compensation scheme. Finally, set-based design requires upfront time of all relevant stakeholders, which is difficult to arrange, especially when so many of them are working on multiple projects at once.

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