

SETPLAN: A COMPUTER TOOL TO AID IN SET-BASED DESIGN

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ABSTRACT

This paper describes a computer tool named SetPlan that works with Building Information Modelling (BIM) software to aid in set-based design. It captures information from a BIM model and displays it in a ‘dashboard’ that supports project participants in developing shared understanding of rebar objects as the design unfolds. In turn, updates from SetPlan help to colour code the BIM.

We engaged practicing structural engineers, rebar fabricator-placers, and general contractors from the San Francisco Bay Area in workshops to determine the need and use cases for SetPlan. This paper illustrates SetPlan’s use for designing a shear wall. SetPlan compares three shear wall reinforcement schemes (representing various wall shapes with different boundary reinforcement). It extracts information from a BIM in Tekla 14.0 about the shear wall reinforcement, enabling information sharing across the project team. The tool eliminates some of the jargon issues that may arise in cross-disciplinary design conversations by displaying data graphically and it is a first step in making set-based design easier to implement using current design software.

KEY WORDS

Set-based design, rebar, building information modelling (BIM), reinforced concrete.

INTRODUCTION

To support lean project delivery, the project team must “collaborate, really collaborate” (Macomber 2005) from the project outset. Collaboration promotes the development of synergistic relationships and a shared understanding of the project among team members. Building information modelling (BIM) can help to develop this shared understanding by allowing the team to visualize the project in 3D and share information about objects in the model. BIM models can show multiple alternatives for a given object(s), allowing project teams to consider sets of alternatives rather than a single alternative, thereby supporting a set-based approach to project design and management (e.g., Parrish et al. 2008a; Ward et al. 1995).

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This paper discusses the development and uses of SetPlan, a computer-based software tool that highlights differences between design alternatives using information from a BIM model and practitioner input. The tool delivers proof of concept that project teams can use a set-based methodology to design a reinforced concrete structure, as illustrated here with a shear wall design example. SetPlan illustrates that software can aid in implementation of set-based design by automating some of the tasks required to consider sets rather than points. SetPlan extracts information about alternatives from a BIM model. Further, it can write information back to the BIM model to illustrate differences between alternatives, allowing participants to discuss value trade-offs, with value propositions (Parrish et al. 2008b) or other means. This paper shows how SetPlan highlights differences between shear wall alternatives, thereby providing information project teams to make decisions about which alternative is preferred, e.g., using Choosing By Advantages (Suhr 1999).

RELATED WORK

SET-BASED METHODOLOGY

Set-based design is a methodology whereby a designer (or team) considers sets of design alternatives (rather than a single ‘point’ design) and postpones commitment to a specific design until they can confidently eliminate the alternatives. Set-based design requires information from various project team members, and is thus best supported in a collaborative design environment (Parrish et al. 2007; 2008a). Set-based design methodologies have been pursued in a variety of domains, including data interpretation to infer protein structures (Altman and Jardetzky 1986) and construction site layout (Tommelein et al. 1991). It has been used in new product development by Toyota engineers (Kennedy 2003; Sobek II et al. 1999; Ward 2007; Ward et al. 1995). Toyota’s approach has inspired the development of a set-based methodology for rebar design (Parrish et al. 2007; 2008b) as presented there, and SetPlan seeks to aid in its implementation.

SET-BASED DESIGN AND PARAMETRIC DESIGN

BIM tools use parametric design “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). BIM tools combine parametric relations with databases of pre-defined building objects to generate 3D models (Eastman et al. 2008). Representations used in both parametric and set-based models define objects by specific attributes, rather than as specific pieces. They use similar operators (e.g., union, intersection, and difference) to define new objects and sets, respectively, and monitor how these new ones relate to previously-defined objects and sets. However, parametric design works with pre-defined objects and relations between them, while set-based design accommodates more open-ended sets and ignores relationships between sets if necessary.

Software that supports collaborative Architecture/Engineering/Construction (AEC) design, e.g., BIM software, makes use of both set-based and parametric design concepts. Lottaz et al. (1999) discuss use of a constraint-based approach to manage the fabrication of beams for a steel frame building with ductwork holes cut into them. They suggest that all project team members use an internet-based collaborative tool to

communicate and collaborate throughout the design process. Their tool for structural steel beams considers the input of different project participants, as does SetPlan; however, SetPlan also writes information to a model, unlike the internet-based tool that Lottaz et al. discuss.

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. Wong et al. (2007) extend this concept to a simulation program for sharing rebar information. Both systems support a reduction in total project time as a result of new methods of communication in the design process.

Nahm and Ishikawa (2006) develop parametric design software to aid in structural engineering. Their program uses a ‘preference set-based design model’ to search a database of possible design alternatives and selects a subset of alternatives based on user inputs. The program prompts for user input to compare alternatives, and user preferences dictate how design progresses. SetPlan also reflects user preference, but it compares user-input alternatives, rather than searching a database of alternatives.

DESIGN OF SETPLAN

OVERVIEW OF SETPLAN

Practitioners involved in our research span the rebar supply chain. They shared their perspectives on value propositions used to make design decisions (Parrish et al. 2008b). 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 be used with SetPlan to assist project teams in developing a 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. SetPlan supplements the spatial and material information contained in a BIM model with this value proposition information (Parrish et al. 2008b). It works side-by-side with existing BIM software (Tekla 14.0) so information such as rebar counts can be extracted from the BIM model. Moreover, SetPlan shares information about rebar fabrication during design that is typically not available until the construction team is selected. For example, SetPlan writes information to the BIM model about whether or not a bar can be bent with an automatic stirrup bender and placing productivity data. The information presented in this paper is typical but does not reflect specifics from any one fabricator. For SetPlan to be most useful, it should include specific information about the preferences and capabilities of the structural engineer, fabricator, and placer on the project team and use this information during the design phase to influence design decisions. SetPlan makes information from the rebar fabricator, placer, and structural engineer explicit and visual, helping them to develop shared understanding and avoid some jargon issues.

IMPLEMENTATION DETAILS

We used Microsoft .NET C# to program the set-based design tool. 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 modelling

software, provided the model supports reading and writing the required information. The Tekla Structures 14.0 .NET Open API makes this information readily accessible. 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 1 shows how SetPlan integrates with Tekla Structures 14.0 and the rebar design and delivery supply chain.

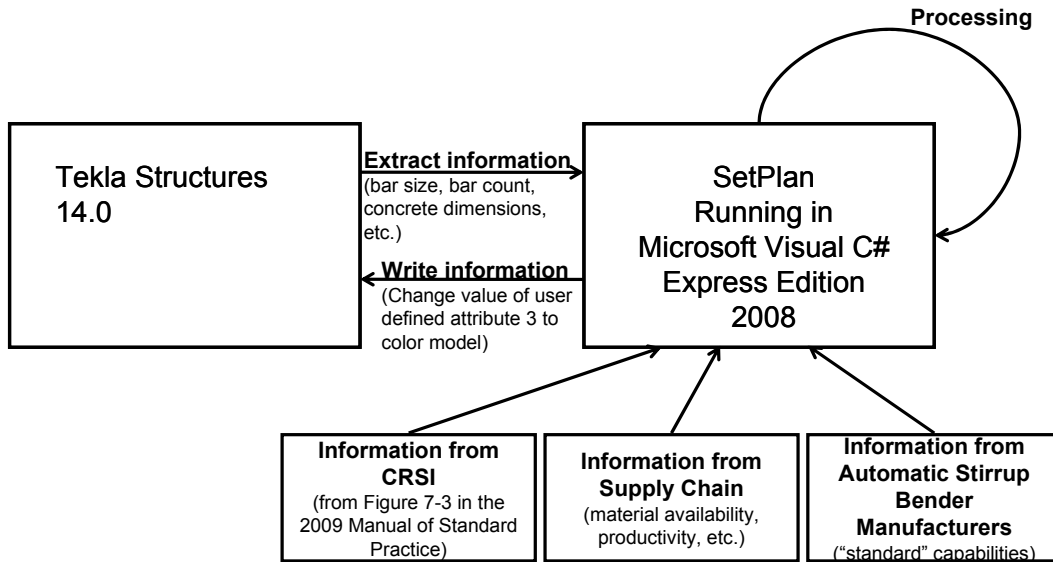


Figure 1: Architecture of the SetPlan Set-Based Design Tool

INFORMATION REQUIRED IN THE MODEL

SetPlan gathers information in the BIM model 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. When users draw rebar in the Tekla Structures 14.0 model, they usually do not specify the rebar’s function (i.e., long-direction tie, short-direction tie, etc.). To use the BIM model with SetPlan, however, they must input this metadata into Tekla Structures 14.0 in the “Name” field of an object’s properties as SetPlan searches this field to determine bar counts. Table 1 lists the object names SetPlan searches for, their physical meaning, and their API Object Class. Figure 2 shows a shear wall with objects labelled according to their function.

Structural engineers require some information during design not necessary for rebar fabrication or placement (e.g., total area of rebar required in an element). They 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 wall 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 fabricators, but it is essential for completing a structural engineering analysis and design. For the model to be 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 (conditions that each alternative must meet), attributes, and alternatives for shear wall design (Parrish and Tommelein 2009).

Table 1: 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	Curtain wall horizontal rebar	SingleRebar
CV	Curtain wall vertical rebar	SingleRebar

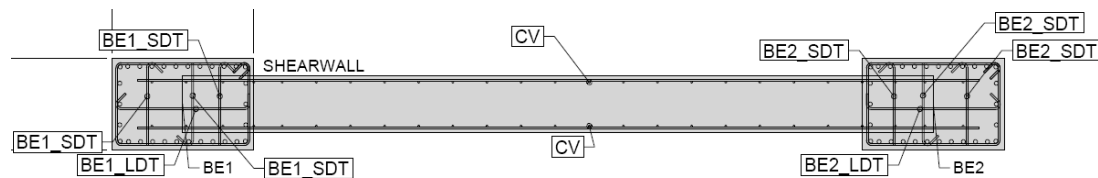


Figure 2: Labelled Shear Wall

Conversely, fabricators require 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, available in 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.

INFORMATION REQUIRED OUTSIDE THE MODEL

SetPlan furthermore requires information from outside the model. Figure 3 shows SetPlan’s main window that displays information about the shear wall design. The top 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. The lower-left corner shows dimensions of each object, 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 also shows bar sizes and concrete strengths for the boundary elements and the wall. The lower-right corner shows SetPlan’s status.

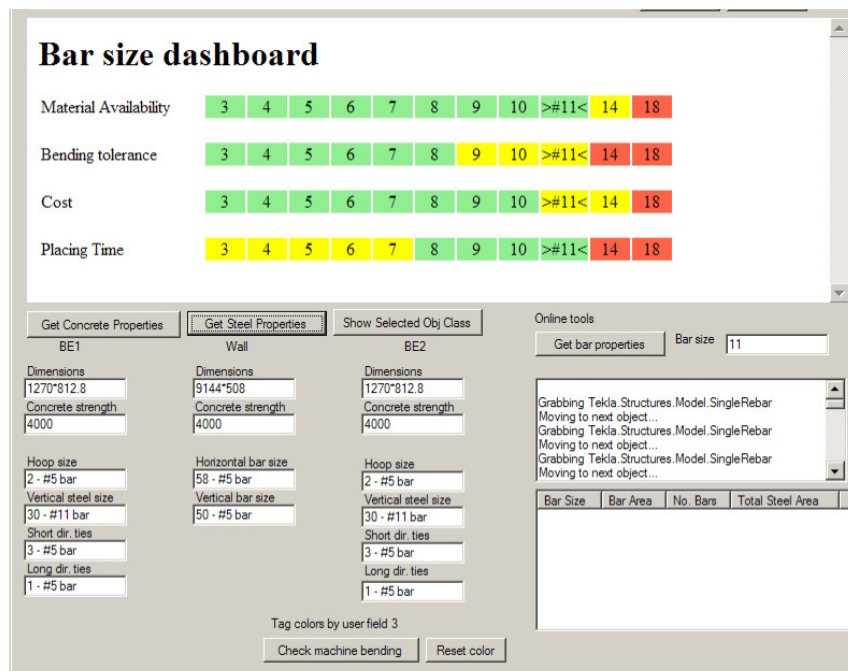


Figure 3: SetPlan's Main Window

Delineations between colours 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 as shown is the case for bar sizes #10 [US #3] through #36 [US #11]. Mills run #43 [US #14] bar less frequently than the other sizes, and #57 [US #18] bar 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>) differ in their bending capabilities. Thus, the colouring 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 #36 [US #11] and larger because placing these requires cranes instead of hand placement. Colouring 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 colouring on the dashboard to reflect their capabilities.

Figure 3 includes a 'Check Machine Bending' button that colour-codes the BIM model according to whether or not a bar can be bent with an automatic stirrup bender.

USING THE MODEL FOR ADDITIONAL VISUALIZATION

We 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 #25 [US #8] bars; however, most automatic stirrup benders cannot bend bars larger than #19 [US #6], so SetPlan uses #19 [US #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 pp. 7-5), provided the total spacing between bends does not exceed 1 m [~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 colour-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 colours of the objects based on the UDA value. Colouring objects to display value proposition information can be extended to show other pieces of information (e.g., congestion, whether or not an object can be prefabricated, etc.). Colour-coding objects makes visualizing differences in alternatives straightforward, and colours can be manipulated from within Tekla Structures 14.0’s model space. Colours display information in a common platform and can illustrate the impacts of choosing one alternative over another.

PROOF OF CONCEPT: SHEAR WALL EXAMPLE

Shear walls resist lateral loads in a structure. Structural engineers commonly use them 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, which often creates 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.

Figure 4 shows three shear-wall design alternatives, all of the same length of 798 cm (314 in). Shear wall A is a dogbone. The wall is 51 cm (20 in) wide, and the boundary elements are 81 cm (32 in) wide and 127 cm (50 in) long. The boundary elements of shear walls B and C are as wide as the walls themselves. Shear wall B is 66 cm (26 in) wide. Its boundary elements are 127 cm (50 in) long. Shear wall C is 51 cm (20 in) wide, and its boundary elements are 203 cm (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.

Visualizing the shear wall design alternatives allows the project team to see differences between the alternatives that may not otherwise be obvious. For instance, the difference in boundary element length may not be obvious in narrative form, but it

is clear in the drawing. To further aid in understanding differences between alternatives, users may elect to colour-code the set of shear wall alternatives. Figure 5 shows the colour-coded set of shear wall design alternatives. Green indicates a piece of rebar can be bent with an automatic stirrup bender. The boundary-element hoops can be bent with an automatic stirrup bender for every shear wall. Long-direction ties can also be bent with an automatic stirrup bender for every shear wall. The short-direction ties cannot be bent with an automatic stirrup bender for any shear wall. Yellow indicates straight bar, which is the case for all curtain steel.

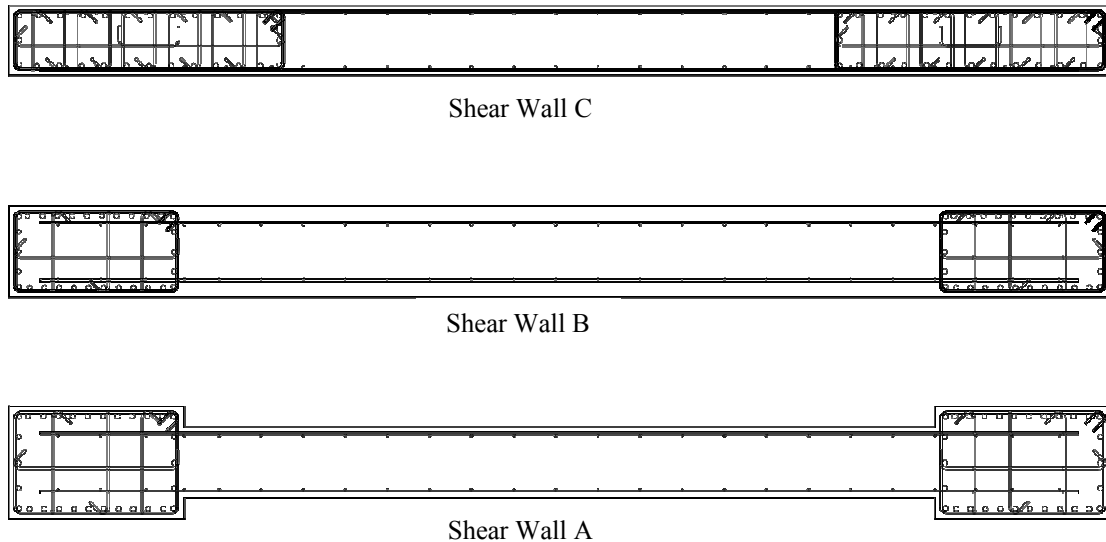


Figure 4: Set of shear wall design alternatives

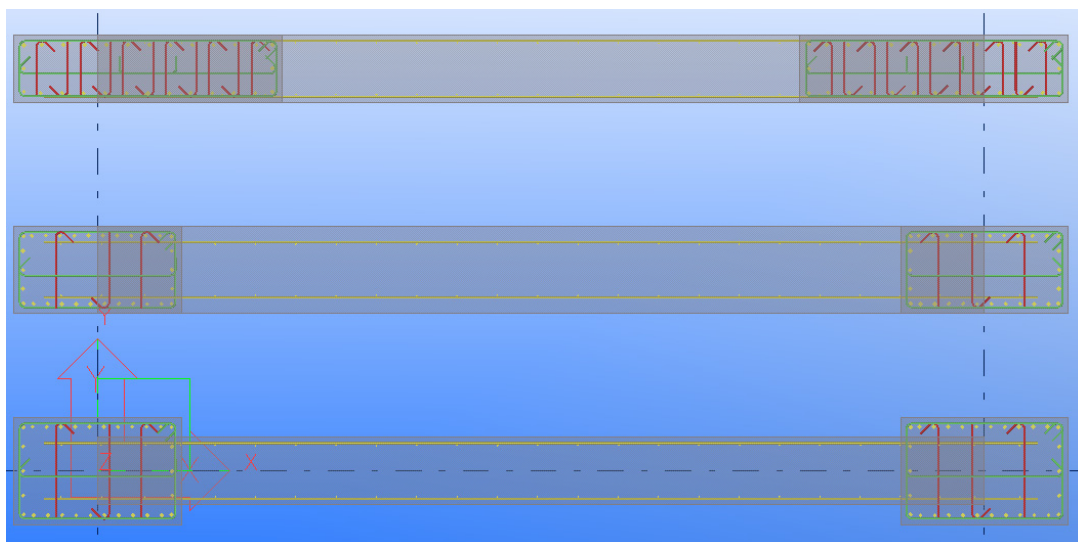


Figure 5: Colour Codes Shown Inside the Modelling Software

In colour, differences between alternatives become clear. Project participants can *see* the impact of a given design decision in terms of ability to table bend bars. Practitioners involved in this research commented this tool could be very useful in practice, as it brings issues to the fore for the project team to discuss. For instance, a

structural engineer 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, that have hooks on only one end cannot be table bent. 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 an understanding of value tradeoffs associated with each alternative.

CONCLUSIONS

Set-based design requires project teams collaborate to develop alternatives and subsequently evaluate them. Practitioners involved in this research articulated the need for a tool to aid in the implementation of set-based design. This paper presented a tool that supplements BIM software with information about rebar fabrication and availability. Further, the tool to highlights differences between alternatives through colour coding the model. This tool colour codes according to whether or not rebar can be table bent; future tools could colour code based on other criteria.

BIM models can help project team members develop shared understanding. They can illustrate alternatives and the differences between them. Visualizing these differences offers project teams an opportunity to discuss value tradeoffs between alternatives. Visualization also provides a common language for design conversations, eliminating some of the jargon issues between participants. Through these design conversations, project teams can make more informed design decisions.

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