VALUE PROPOSITIONS FOR SET-BASED DESIGN OF REINFORCED CONCRETE STRUCTURES

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ABSTRACT

Reinforced concrete is used in capital facilities in all sectors of the construction industry. Numerous specialists are involved in its design and supply chain. However, reinforcing steel (rebar) configurations are typically specified by structural engineers relatively early on in the project, often without the benefit of input from project stakeholders such as rebar detailers, fabricators, and placers. In current design practice, using tacit knowledge of structural performance as well as construction expertise, structural engineers select a rebar configuration that is optimal from their perspective, given the project constraints. The adoption of new design methodologies, such as performance-based design and set-based design, affords opportunities for use of the knowledge of downstream project stakeholders in structural design. Value propositions 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 mutual understanding while gauging the merits of different sets of alternatives, making tradeoffs, and narrowing sets of design alternatives. Industry participants in this research have helped to develop such value propositions. This paper presents a value proposition of a rebar placer, that relates rebar diameters to labour productivity rates, and these can be translated into placement costs. Proof-of-concept is delivered of the use of this value proposition in set-based design of a reinforced concrete shear wall.

KEY WORDS

lean construction, set-based design, performance-based design, reinforced concrete, rebar, design methodology, value proposition, stakeholder value, constructability, cost

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INTRODUCTION

Current practice in design of reinforcing bars (rebar) for concrete structures is to use a point-based methodology. That is, following a schematic design phase, the structural engineer designs a specific rebar configuration and that selection (or point) is refined throughout the design process as more detail is developed and potential clashes are detected. Point-based methodologies are sequential in nature; the structural engineer first designs the rebar, then that design is given to the general contractor and then, in turn, it is given to the concrete and rebar subcontractors. Each of these project stakeholders may request a change in the design. However, the structural engineer does not necessarily find out why such a change is requested unless they are told the design cannot be constructed as is. Thus, stakeholder best practices and preferences are not necessarily documented as such, which means that they tend to not get used to compare alternative designs and they do not get incorporated into future designs. By contrast, a set-based methodology supports early involvement of all project stakeholders (Olander and Landin 2005) so that their unique knowledge and expertise may be used in developing a design. Project stakeholder values may or may not align, but in either case, value propositions are worth articulating in order to provide a rational means of decision making.

Value propositions spell out relationships between what matters to whom and why. They provide a means for a project stakeholder (a person or a group) to characterize product or process features (e.g., range of technical feasibility) or make its (their) knowledge, know-how, skills, capabilities, and values explicit for their own use or to communicate it to other project stakeholders. Xu et al. (2006) discuss the need for knowledge capture for future use; value propositions capture the knowledge and values inherent to each project stakeholder for use in current and future projects. Isaac and Navon (2008) discuss the importance of impact assessment due to design changes; value propositions help to develop understanding of how design changes may impact stakeholders.

In this paper, we introduce one example value proposition from a rebar placer. This value proposition compares rebar size to labour productivity rates for a specific structural element, thereby allowing the designer to narrow sets of design alternatives and make choices during schematic design or design development that are informed by the placer’s expertise and practice (based on past projects and current capabilities). Further, the value proposition can be used throughout the design and construction process to evaluate the impact of a design change on the placer’s productivity, which in turn may affect cost and schedule.

RELATED WORK

REINFORCED CONCRETE DESIGN

Reinforced concrete design consists of sizing concrete members to resist the design loads of a structure. Once the members are sized, a *reinforcement ratio* ρ, comparing rebar area to concrete area is used to determine the area of rebar needed for a member, A_s. The American Concrete Institute (ACI 2005) mandates that ρ be between .01 and .08 to maintain resistance to bending and constructability, respectively. After having determined A_s, structural engineers are responsible for designing rebar layouts for given members in order to achieve the necessary strength and ductility in that member mandated by relevant codes (e.g., Eurocode 2, ACI 318, Building Code of Australia). A structural engineer pins down a specific rebar configuration to meet the calculated rebar demand, A_s. This choice is informed by the engineer's experience and judgment including rules of thumb; however, there is no single *right* way to design rebar. Often there are many solutions that satisfy the requirements; on occasion the problem is over constrained.

SET-BASED METHODOLOGY

Set-based methodologies have been developed and are used in the new product development community. Toyota's methodology has inspired the research presented here. Ward et al. (1995) and Ward (2007) describe set-based concurrent engineering as a key component of the success of Toyota. Toyota's ability to consider more alternatives for longer in the product development process than many of their competitors characterizes their set-based methodology. Sobek et al. (1999) explicitly defined the principles of Toyota's set-based concurrent engineering.

Parrish et al. (2007) developed a set-based methodology for rebar design. Their canonical beam-column joint example illustrated the steps of set-based rebar design: (1) Identify decision units, (2) Map design spaces, (3) Find compatible combinations, (4) Weigh alternatives, (5) Commit, (6) Document decisions. Set-based design can be used throughout the design process, and as such, the granularity of the design must increase. Thus, a first step in set-based design is to identify what level of decision is necessary at the given phase (e.g., general building shape, choice of structural system and material(s), column size, rebar configuration). Mapping of the design space ensures that all structurally feasible options are considered. Once all options are determined, they need to be communicated to the project stakeholders for their input. The third step involves using the expertise of the project stakeholders to determine which design options are compatible. The fourth step is for stakeholders to evaluate feasible options yet defer eliminating those that are less desirable from their perspective until they reach the last responsible moment to do that. The fifth step is for the team to determine which design to commit to. Finally, the sixth step is to ensure that the derivation of this decision is documented for future use. These steps promote a more globally-optimal design and avoid the rework (incl. backtracking) that is characteristic of a point-based methodology.

VALUE PROPOSITIONS: CONCEPT

Conceptually speaking, value propositions allow for each project stakeholder to understand the value tradeoffs within their own specialty and consider those of others. David Mar, a structural engineer in the San Francisco Bay Area, illustrated his thoughts on the need to articulate and communicate value propositions associated with different designs at a research workshop with the authors in December 2006. Figure 1 illustrates his concept of a value proposition in comparing two options for the design of shear walls. Option A is more efficient than Option B from a structural engineer's 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 tends to make rebar placement more straightforward. However, Option B is thought to be better for building occupancy because it provides more floor space and exposed perimeter (potential window and door penetrations, etc.). Option 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 Option A and (2) rebar congestion in Option B increasing labour costs. The questions are: How much more valuable is Option B than Option 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 make the balance tilt in favour or Option B as it has a smaller formwork contact area and a smaller concrete volume.

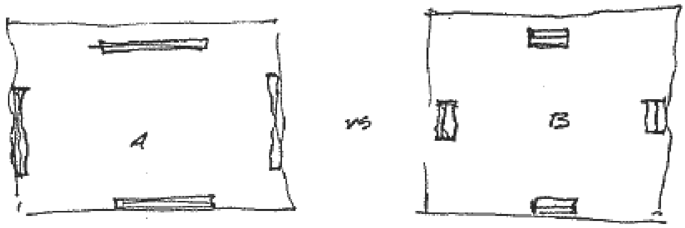

Figure 1: Comparison of Shear Wall Designs for Option A vs. Option B (Mar 2007)

To tackle how to express the relative value of Option 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 2 conceptually depicts the relative labour 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 3 conceptually depicts the relative labour 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 2). 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 options 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 Option A ('des A'), it would be more cost effective to use double layer rebar rather than a single layer of rebar.

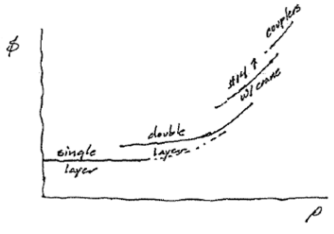

Figure 2: Rebar Value Proposition Concept for Beams (Mar 2007)

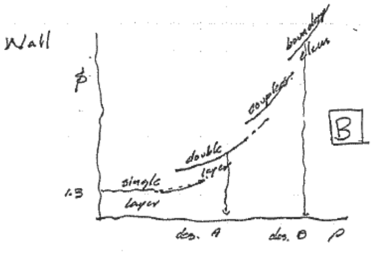

Figure 3: Rebar Value Proposition Concept for Walls (Mar 2007)

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 a range of values for it. 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 our research team talk about a design in terms of Structural Activity Codes (SACs) (details on these are given later in this paper). At an early research 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.’

VALUE PROPOSITIONS: ROLE IN THE DESIGN PROCESS

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 conceptual and schematic design phases. The structural engineer designs the structure by preferred means to meet the constraints that are known during design (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 detailing, 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, esp. those brought on board late, then often leads to negative iteration in design and causes rework (Ballard 2000). 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.

Rather than on hard-bid projects, we see value propositions being used on projects with integrated project teams (Lichtig 2006; Farrow 2007; Matthews and Howell 2005). In the integrated project team environment, project stakeholders are available for direct consultation throughout the design process. 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 it 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. Should a mechanical subcontractor later ask to cut through a beam, the team can use the value proposition to determine whether the better decision is to ask the mechanical subcontractor to re-route a pipe vs. redesign the beam with different reinforcement.

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 1 shows a partial list of common SACs. Labour rates are associated with each of the different SACs for various bar sizes, usually expressed in units of kg/worker-day [lb/worker-day]. Structural engineers and design cost consultants estimate preliminary costs for rebar but do not take SACs into account; rather, these estimates are based on aggregated steel weight alone. Value propositions add nuance and help to mitigate these discrepancies by illustrating the different relative costs of rebar placement within a given SAC. Each SAC has its own value proposition. The value proposition would be very difficult to read if it compared different SACs, bar sizes, and bar types on one graph. To compare different SACs, multiple value propositions need to be compared.

Table 1: Structural Activity Codes (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 2: Bar Numbers, Areas, and Diameters (CRSI 2006)

Bar No. (English)	Diameter, mm (in)	Cross-Sectional Area, mm^2 (in^2)
#10 (#3)	9.5 (0.375)	71 (0.11)
#13 (#4)	12.7 (0.500)	129 (0.20)
#16 (#5)	15.9 (0.625)	199 (0.31)
#19 (#6)	19.1 (0.750)	284 (0.44)
#22 (#7)	22.2 (0.875)	387 (0.60)
#25 (#8)	25.4 (1.000)	510 (0.79)
#29 (#9)	28.7 (1.128)	645 (1.00)
#32 (#10)	32.3 (1.270)	819 (1.27)
#36 (#11)	35.8 (1.410)	1006 (1.56)
#43 (#14)	43.0 (1.693)	1452 (2.25)
#57 (#18)	57.3 (2.257)	2581 (4.00)

REBAR BENDING SPECIFICATIONS

The Concrete Reinforcing Steel Institute (CRSI 2003) classifies bars as either straight or bent. Bent bars are classified as light bending, heavy bending, or special bending with the following definitions. Table 2 (CRSI 2006) converts bar sizes to bar diameters and cross-sectional area expressed in metric and English units.

A. LIGHT BENDING. All #10 [#3] bars, all stirrups and ties, and all bars #13 through #57 [#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 300 mm [12 inches] or more to outside of bar.

B. HEAVY BENDING. Bar sizes #13 through #57, [#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 *Manual*), all radius bending in more than one plane, all multiple plane bending containing one or more radius bends, and all bending for precast units.

SHEAR WALL EXAMPLE

The example of reinforcing a concrete shear wall illustrates the use of a value proposition. 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, we consider only the interactions between the structural engineer (SE) and the rebar placer (placer). Shear walls are used in reinforced concrete structures to resist the lateral forces imposed on structures,e.g., during an earthquake. In California, reinforcement in shear walls can get very dense, causing concern for constructability. Value propositions can inform the rebar design process by presenting means to more objectively assess fabrication and construction concerns.

The shear wall examined in this paper is based on a design example in an introductory concrete design textbook (Nawy 2000). This shear wall is designed according to ACI 318 (ACI 2005) for a 12 storey structure that is 45 m (148 ft) high with equal 6.7 m (22 ft) bays. Loads on the shear wall are (1) A factored gravity load of W_u = 21.4 MN (4,800,000 lbf), (2) A factored moment at the base of the wall due to seismic loads (from lateral analysis) of M_u = 62.6 MN-m (554 x 106 in.-lbf), (3) The maximum axial force on the boundary element, P_u = 20 MN (4,500,000 lbf), and (4) The horizontal shear force at the base, V_u = 3940 kN (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 GC, the owner's agent, and the architect prior to reaching the SE.). Thus, the value proposition primarily assesses impact of decisions during the design process. Figure 4 shows a plan view of the shear wall. The SE designs a shear wall to meet the demands as were listed.

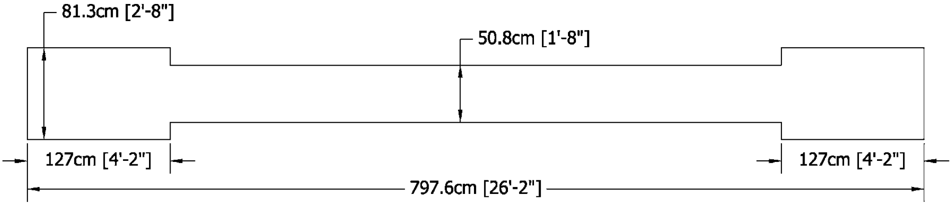

Figure 4: Plan view of the shear wall (redrawn from Nawy 2000)

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, specific rates in Figure 5 are fictitious but they have been 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 region. The placer's value proposition for rebar placement in shear walls is expressed in terms of relative labour productivity rates (rather than in terms of relative cost). Increasing the bar size increases the productivity rate for #10 (#3) to #43 (#14) bars. However, productivity rates decrease when upsizing from #43 (#14) to #57 (#18) due to the weight and diameter of the #57 (#18) bar. Figure 5 illustrates that placing straight bar is more productive than placing light or heavy bent bar. This is one reason why placers in this region seldom use #10 (#3) rebar in commercial building construction.

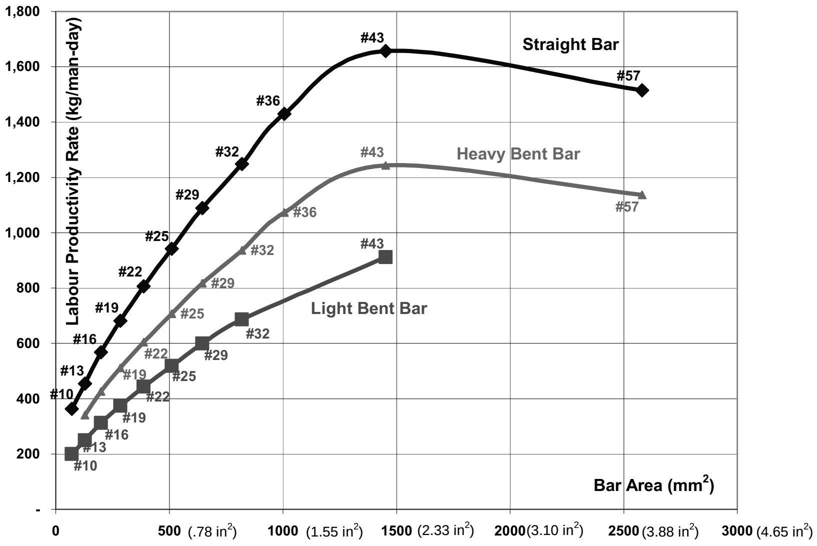

Figure 5: Rebar Placer's Value Proposition for Shear Walls

USE OF THE VALUE PROPOSITION IN SHEAR WALL DESIGN

The SE can use the placer's value proposition as a design aid. Clearly, it is advantageous in terms of labour productivity to use #43 (#14) bars if at all possible (assuming a crane is available to handle such heavy rebar). SEs often try to minimize the total weight of rebar in a project. As rebar is priced by weight, it is reasonable to try to minimize the total weight in a project, as this reduces material costs. However, the savings in material cost may be outweighed by the extra labour costs associated with having to place a larger quantity of lighter bars. The value proposition can be used in this example to objectively evaluate the difference in labour productivity rates for different longitudinal bar sizes. The cost savings associated with a productivity increase is likely a straightforward calculation for the placer. The SE can compare the cost savings associated with productivity gains to the additional cost of more steel. Decision making based on facts found 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, it would seem that the logical choice is to use enough #43

(#14) bars in the longitudinal direction to achieve the required A_s, 297 cm^2 (46 in^2), which turns out to be 28 bars in this case. However, this is not an acceptable option as the #43 (#14) bars have diameters that are too large to satisfy ACI 318's rebar spacing requirements. Thus, the next logical choice is to reinforce the shear wall with #36 (#11) bars in the longitudinal direction. Figure 6 illustrates the final rebar configuration selected. The shear wall boundary elements are reinforced with 30 #36 [#11] bars vertically. Heavy bent #16 [#5] closed hoops are used for transverse steel inside the boundary elements. #16 [#5] bars @ 30.5 cm [12"] on centre are used in both directions for reinforcement curtains in the rest of the wall.

Schedule impacts due to the increase in productivity rate can be assessed using value positions as well. Rebar placement precedes various activities; it may or may not be advantageous to do it as fast as possible, or with the highest possible labour productivity rate, as the merits thereof depend on how fast the project can progress in general.

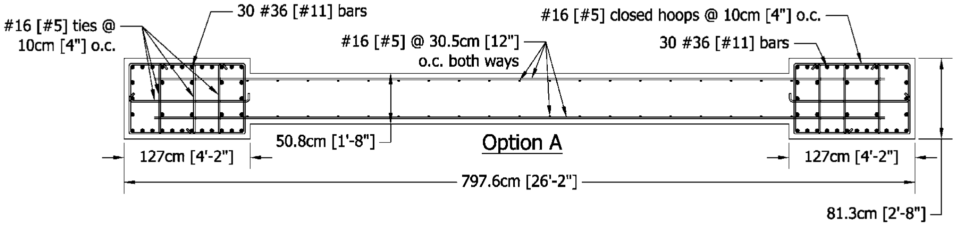

Figure 6: Detailed Plan View of the Shear Wall (redrawn from Nawy 2000)

CONCLUSION

This paper 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 is best supported by means to rationally weigh stakeholder values against one another. 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, rules of thumb are used to make decisions. Unfortunately, these do not necessarily reflect relative value, and thus may lead to a decision that is not optimal for the project. Value propositions focus on relative value of alternatives, and are more nuanced than rules of thumb are.

This paper presented an example of a value proposition, developed in conjunction with San Francisco Bay Area fabricator-placers. Although the numbers presented are fictitious, the trend is supported by data from Bay Area firms. Further study is necessary to develop a full suite of value propositions as well as to understand how to best use them for set-based design in a collaborative team setting.

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 another placer's input on a subsequent 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 or estimating, when pencils are to be sharpened, one needs to engage in the conversation real people with their value propositions based on their own data.

Research remains to be conducted to determine how value propositions could be used in conjunction with existing design strategies and tools including Building Information Modelling (BIM), integrated project teams, supply chain management, risk management, and lean procurement strategies.

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