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CAPABILITY-BUILDING FOR CONSTRUCTION INFORMING DESIGN

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ABSTRACT

The research question is whether Takahiro Fujimoto's theory of capability-building to create the Toyota Production System (TPS) is useful to understand the creation of a capability for Construction knowledge to inform design (CID). This paper attempts to reveal what was done in sufficient detail to compare it against Fujimoto's explanation of how Toyota's capability-building created TPS. The method used was to create and analyze data using the Fujimoto framework explained in his book, *The Evolution of a Manufacturing System at Toyota*. Fujimoto's theory allowed the authors to confirm that Toyota-style capability was created and delivered a significant competitive advantage in 2 of 4 projects where CID was attempted. The capability was created without knowledge of Fujimoto's theory of Toyota's capability-building. As with previous studies, it was impossible to identify routines developed to implement the process steps. It was also not possible to distinguish process steps for learning from others for production. Industry fragmentation is an obstacle to the level of integration this capability requires of designers and builders. The capability for construction knowledge to inform design can be created and requires vision and leadership to challenge the traditional design process.

KEYWORDS

Theory, capability, autoethnography, emergence, evolutionary.

INTRODUCTION

This paper is autoethnographic research about building capability to solve the problem of late and insufficient construction knowledge to inform design as it develops, especially early. The first author is the ethnographer, and the second author is the participant entrepreneur, designer, and manager of the capability-building, reflecting on his experiences to report what transpired. The third author, another ethnographer, has prior experience with this specific capability-building in the nuclear industry, but for this paper has focused primarily on the communication strategy and next steps for the general construction industry. Although conceived to test through Action Research, the research methodology is a variant of autoethnography, specifically "layered accounts," which is "author's experience alongside data and abstract analysis, and relevant literature." (Ellis et al. 2011) The research is post hoc looking back on experience considering a method that was not known to participants at the time.

The purpose of the research is to determine whether and how Takahiro Fujimoto's explanation of how Toyota continually improved is useful for leaders trying to do that within Construction. The real-world problem is the architects and engineers design without builders'

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knowledge of construction constraints. The supply chain requires design intent before builders, fabricators, and product suppliers are procured, which limits the possibility of using Design for Manufacture and Assembly (DfMA) principles (Pasquire and Connolly 2003). Currently, design is conveyed through documents without a rigorous constructability review, leaving the Request for Information (RFI) process as the only mechanism for the general and trade contractors to call attention to problems and offer solutions. BIM clash detection is then started without alignment between design/engineering, and fabrication and assembly information. Preferred building methods, especially prefabrication, are not reflected in the design and the opportunity for design innovation that would create cost and schedule savings is lost.

The second author realized this several years ago while working as a designer on a Design-Build project and decided that he wasn't going to detail solutions that would become obsolete once the build partner was brought on board. He decided to focus on conveying design intent between systems and allowed the trades' subject matter experts to help drive overall constraints of the building systems and provide details that they could build, creating cost savings and innovations in overall design of the building.

After joining a large U.S. General Contractor (GC) as a Virtual Design and Construction (VDC) specialist, the second author, the "protagonist" in this story, was asked to assist a Design-Build student housing project team implementing a prefabricated structural cold-formed steel stud wall panel and flooring system in which the GC team was committed to informing the design team about constraints in the prefabrication process. The dormitories were very repetitive, so the protagonist selected a corner of one of the middle floors and set some clear objectives to work through for 6 weeks, including: trade partners preferred details, and the coordination of a detailed model in that strategic location. The decisions made during this process were then scaled across the project in early design phases. During this work he created templates to use across the GC's multiple offices throughout the country. Figure 1 shows this process.

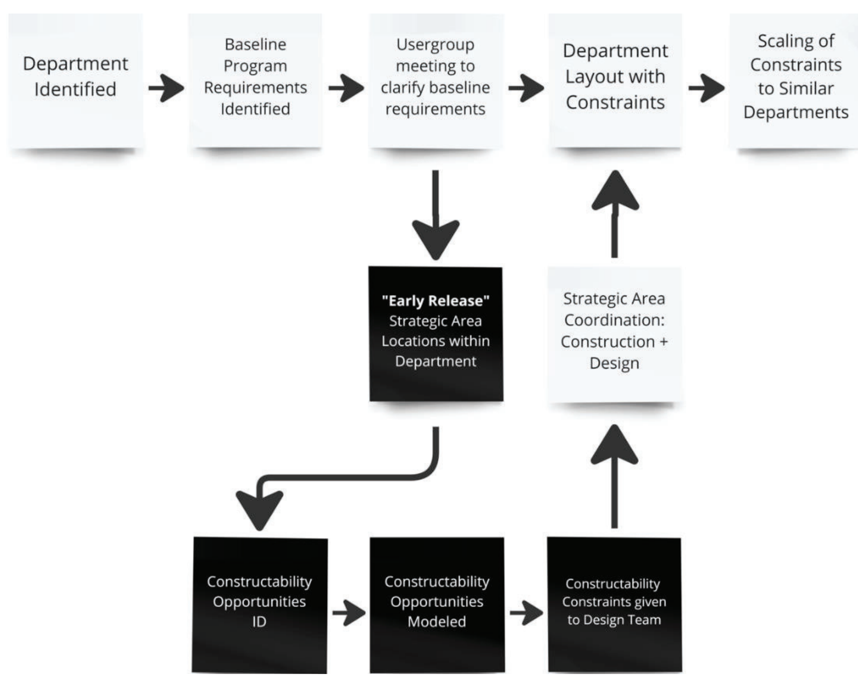

Figure 1: Typical Construction Informing Design Workflow

This typical workflow for Construction Informing Design is intended to be repeated through multiple typologies that exist in a project. Incrementally releasing functional program for strategic in-depth analysis creates the opportunity for programming, conceptual design, and constructability to happen concurrently. Key release points at user group review meetings and initial department layouts, as depicted in Figure 1, are critical to the success of this process and trigger key consolidation points to incorporate constructability constraints into the design.

Based on this experience, the authors decided to research whether and to what extent Takahiro's explanation of Toyota capability-building could explain what transpired on the 4 projects on which the second author organized project teams to enable Construction to Inform Design. This paper is an attempt to answer that question.

LITERATURE REVIEW

The only reference to Fujimoto the first author found prior to initiating a prior study reported in a 2019 IGLC paper was in a 2001 IGLC paper titled "System View of Lean Construction Application Opportunities" by Flavio Picchi (2001). He noted Fujimoto's evolutionary perspective starting from 3 levels of manufacturing capability anchored in routines for manufacturing, learning, and developing new capabilities by combining ones already developed. Niklas Modig and Par Ahlstrom also mention these 3 types of Toyota capability in their book, *This Is Lean* (Modig and Åhlström 2012), and point to Fujimoto's explanation of how the Toyota Production System emerged through trial-and-error capability-building. Their praise led the first author to read Fujimoto' book, *Competing to Be, Really Really Good* (Fujimoto and Miller 2007), followed by *The Birth of Lean* (Shimokawa and Takahiro Fujimoto 2009), a compilation of interviews with men who worked alongside plant manager Taicihi Ohno, and finally *The Evolution of a Manufacturing System at Toyota* (Takahiro Fujimoto 1999), all of which are essential to undertake researching Toyota-style capability-building. However important these are, the first author needed Mike Rother's explanation of Toyota's improvement and coaching practices, "katas," (Rother 2010) to develop the research methodology used in this and 3 previous IGLC papers. (Berg and Reed 2019) (Berg et al. 2020) (Reed et al. 2021)

THEORETICAL FRAMEWORK

This research uses Fujimoto's definition of organizational capability as the power or ability of an organized group to do something using effective routines. Our work is based on Fujimoto's explanation of how and why Toyota's capability to build capability led to the Toyota Production System (TPS). He begins by explaining that the purpose of building capability for Toyota and other automakers is to become more competitive in the marketplace by solving potential customers' problems better than competitors. According to Fujimoto, the starting point for understanding capability-building is the process steps that become routines for coordination, developing information, or fabricating and/or installing components and assemblies to improve production, and learning to improve processes.

Fujimoto identifies 3 levels of manufacturing capability as follows:

1. Routinized Manufacturing Capability. Its produces competitive performance in a stable environment where necessary prerequisites flow and the product can be made predictably. Its primary characteristics are a firm or project-specific pattern of steady-state and efficient transfer of accurate information.
2. Routinized Learning Capability. It allows for changes or recoveries of competitive performance in a dynamic environment. Its primary characteristics are a firm or project-specific ability of handling repetitive problem-solving cycles or an expected pattern of system changes.
3. Evolutionary Learning Capability. It enables changes in patterns of routines that contribute to capability. Its primary characteristic is the ability of handling system

emergence, i.e., dealing with non-routine patterns of system changes to form new routine capabilities.

TPS-style process steps are comprised of actions that can be measured or assessed against a desired outcome by the people who perform them, which enable learning and improvement. Routines can be effective for safety, quality, accuracy, and production goals, so it's important and often imperative that these adhere to guidelines that allow for inherent human differences. People must be encouraged and rewarded to continually improve these "best practices" as well as to invent better ways to do their work. The role of managers is to ensure that the people who perform the work are provided the training, information, and tools they need in the safest possible environment. The why loop must be closed by managers and performers through assessing whether the capability is achieving the success criteria established as targets. "The Toyota Way" is for people to strive to reach a future state by working towards intermediate target conditions (Rother 2010). This is the engine of continuous improvement.

Fujimoto identified 5 pathways for solving problems, as follows.

1. Rational Calculation: classic product design problem-solving.
2. Environmental Constraints: circumstances negating a usually viable solution.
3. Entrepreneurial Vision: pursuing solutions advocated by leaders.
4. Knowledge Transfer: following the advice of experts within or outside the project.
5. Random Trials: testing a variety of possible solutions.

Fujimoto also defined 4 ascending levels of capability-building within Toyota. The first is system change, activities that lead to change within the system to which a capability contributes. The second level is "Multi-Path System Emergence" when a variety of patterns (sequence and arrangement) in system changes can be seen in combination without a clear relationship between the pattern and content of system changes. Multi-Path System Emergence coupled with routinized capability indicates the capability to build new capability, which Fujimoto named "Evolutionary Learning Capability." As noted above, Fujimoto also defined this as the third level of manufacturing capability, and the key to Toyota's success. Fujimoto identified a fourth, penultimate level of capability-building, which he called "Dual-Layer Problem-Solving." This is when Multi-Path System Emergence and Evolutionary Learning give leaders the opportunity to create new solutions at a higher organization level based on solutions emerging from lower lever problem solving (Takahiro Fujimoto 1999).

RESEARCH METHOD

The method incorporates steps that were not explained by Fujimoto and are necessary to execute TPS capability-building to improve competitiveness in the marketplace. All would be used in Action Research and were used in this autoethnographic research, based on reflection.

The first author asked the questions based on his understanding of Fujimoto's explanation of how Toyota's capability-building led to TPS. The second author, who designated the objectives and process for achieving them and taught these to new members of each of 4 project teams, answered the questions. Reporting on what was done and accomplished for this study, he was able to draw upon project information such Building Information Models, work plans, meeting agendas and minutes, correspondence, schedules, budget, and cost reports. He also kept and could refer to extensive personal notes to answer questions based on the research method described above.

INFORMATION REQUESTED FROM THE PARTICIPANT AUTHOR

1. Identify projects attempting to build and implement the capability.

2. Articulate the "Direction or Challenge" (Toyota Improvement Kata step 1) stated as the purpose.
3. Define the "Current Condition" (Toyota Improvement Kata step 2).
4. Establish the "Next Target Condition" objective, which are the "Competitive Success Criteria" for the capability (Toyota Improvement Kata step 3). (Rother 2010)
5. Identify key people contributing to the new capability and describe their roles.
6. Define the process developed collaboratively with the team by describing each step to achieve the Next Target Condition including the next customer for the step, responsibility, frequency, time span, and expected results.
7. Evaluate "Routinized Capability," the use of process steps by determining the extent each step was used on a 1-5 Likert Scale, step used as intended: 5, strongly agree; 4, agree; 3, neither agree nor disagree; 2, disagree; 1, strongly disagree.
8. Evaluate Competitiveness by assessing the impact of all capability process steps considered together on each of the competitive criteria with each success criteria contributing an equal percentage to the total competitiveness score for the capability on the same 1-5 Likert Scale.
9. Determine "Effective Use." This requires both routinized capability (the sum of steps used equal to or greater than 75%) and "Capability Competitiveness" (capability improvement equal to or greater than 75%) This is outside the Fujimoto framework, done to see the relationship of routinized capability and competitiveness.
10. Identify "Problem-Solving Paths" by answering yes or no to whether each of which the 5 paths to solving problems described by Fujimoto contributed to the capability.
11. Determine "System Change Impact" for only the projects having Routinized Capability by answering yes or no to whether there were changes in the system/subsystem to which the capability contributed, in this case "Constructable Design Development Documents within Allowable Cost."
12. Determine "Multi-Path System Emergence" for only those projects with System Change Impact by first answering yes or no to whether there were variety of patterns (sequence and arrangement) in system changes; and second by answering yes or no to whether a clear relationship between the pattern and content of system changes could be seen. If there was no relationship between pattern and content, there is Multi-Path System Emergence.
13. Determine Evolutionary Learning Capability by answering yes or no to whether Routinized Capability and Multi-Path System Emergence were present.
14. Determine Dual Layer Problem Solving, separate from and regardless of whether there is Evolutionary Learning Capability, by answering yes or no to whether intentional selection and modification of capability solutions to produce new capability to solve other problems could be seen.

DATA

The second author reported the following.

1. Direction/Challenge. CID purpose is for Construction subject matter experts (SMEs) to proactively provide constructability information for building systems and components including procurement lead times, installation durations, cost and schedule impacts, prefabrication possibilities, and BIM details to architects and engineers according to mutually agreed dates in formats that can used to develop construction documents.
2. Current Condition. Architects and engineers design without builders' knowledge of construction constraints.

3. Next Target Condition success criteria stated as objectives are as follows.
    a. First, no unplanned negative iteration in the design process.
    b. Second, content provided by design team has been reviewed and signed off by project member companies responsible for putting the work in place.
    c. Third, design intent dimensioning is in alignment with construction detailing.
    d. Fourth, prefabrication opportunities are incorporated into the construction documents.
4. Key contributors to the capability are as follows.
    a. Preconstruction Manager (PCM). Procurement and financial setup to allow trade partners to engage in the early phases of design. Setup of project estimates to capture strategic deep dive information that will inform overall costs.
    b. Design Manager (DM). Packaging and alignment of client information, designer content, and contractor provided content. Leads early alignment session on timing and overall objectives for the process. Provides example content for similar proposed solutions or leads charrettes to gain team alignment.
    c. Superintendent (SI). Identifies locations in the project or specific program scope that will inform the overall schedule and logistics plan. Sets goals for flow of work and prefabrication approaches that will impact design.
    d. VDC Manager or Senior Engineer (VDC). Sets up the model environment and clearly conveys to the extended team where they should focus in the 3D environment. Creates 3D views and sheets to capture design decisions as they are made and tracks actions in a single location for the team to update in the model.
5. Process steps, responsibilities and Next Target Condition success criteria for projects are shown in Table 2.
6. Table 1 describes the projects on which teams attempted to build and implement the capability and summarizes what transpired.
7. Routinized Capability, the use of process steps, is shown in Table 2 for each the 4 projects studied. Use of process steps reached the 75% threshold for only the first 2 projects.
8. Next Target Condition Competitiveness scores are also shown in Table 2. Three of the 4 CID capability projects substantially improved competitiveness.
9. Effective Use scores are also reported in Table 2.
10. Problem-Solving Paths. All 4 project teams employed 3 of the 5 problems-solving paths identified by Fujimoto: Rational Calculation, Entrepreneurial Vision, and Knowledge Transfer. Environmental Constraints and Random Trials were not used.
11. System Change Impact. The Constructable Design Development Documents within Allowable Cost subsystem, which the CID capability supported, was changed, and improved in the first 2 projects, the ones with Effective Use (high use and competitive scores), but not in the other 2 where it was not achieved.
12. Multi-Path System Emergence. Both projects with System Change Impact displayed a clear relationship between the pattern and content of system changes. Since Emergence is indicated by no clear relationship between the content and pattern of changes, neither could be said to have it.
13. Evolutionary Learning Capability requires Routinize Capability and Multi-Path System Emergence. None of the projects achieved this.
14. Dual Layer Problem Solving. Intentional selection and modification of capability solutions to produce new capability to solve other problems was not visible in any of the projects.

Table 1: Capability Application on Projects

#	Descr	What Worked	Contract Type	Integration
1	Higher Education Student Housing	Builder details incorporated into overall design intent of the project.	Design-Build Guaranteed Maximum Price	The architect and extended team were fully committed to the process.
2	Higher Education Teaching and Learning	Alignment with principal designer early on intent. Trade coordination and Construction Document level information was produced out of the process to inform design.	Design-Build Guaranteed Maximum Price	The team would have liked to continue the process once they were done with the first strategic location was complete on the project.
3	Corporate Office	Detailed trade models quickly identified dozens of design issues and potential design solutions.	Construction Manager at Risk	The architect stopped the process after a few weeks and stated it was too early in the process.
4	Higher Education Healthcare Provider	Alignment with cost program modelling process helped identify building and area specific variables. Detailed pull plans for key work informed overall pull planning activities.	Design-Build Guaranteed Maximum Price	Multiple pauses due to the overall project deadlines and concurrent incremental packages.

Table 2: Use of Process Steps

Step	Description	Who	Prj.1	Prj.2	Prj.3	Prj.4
1	Early alignment with project leadership on approach and execution	DM	5	5	2	4
2	Early alignment on timing of process to inform procurement strategy	PM	5	5	1	3
3	Stakeholders are identified and procured for the duration of the activity	PM	4	5	2	3
4	Extended team alignment on benefit and approach	DM	5	5	2	3
5	Clear program and building areas are defined and known information for the given scope is categorized into a single location	DM	5	3	5	3
6	Standard templates and program data are reviewed and agreed upon as a baseline for design intent	DM	4	5	2	4
7	Model is setup and extended team members models are linked in with matching coordinates	VDC	5	5	2	5
8	Boundaries are clearly defined in 3 dimensions	VDC	4	5	5	3
9	Model updates and tasks are tracked in a single location and shared with the extended team	VDC	4	5	3	1

Table 3: Projects Process Steps Use Summary (continued)

Step	Description	Who	Prj.1	Prj.2	Prj.3	Prj.4
10	Locations variables are identified and labelled	DM	5	5	5	3
11	Overall building systems impacted in each area are identified and labelled	DM	4	2	5	2
12	Overall duration and cadence are set with clear goals at each cadence interval	DM	5	5	1	3
13	Builder details are proposed, and locations are identified within the defined boundary	DM	4	5	3	4
14	Prefabrication opportunities are proposed and identified within the defined boundary	SI	5	5	1	3
15	Cost impacts are estimated for proposed building systems and compared to industry baselines	PCM	4	4	1	4
16	Schedule impacts are predicted for proposed building systems and compared to industry baselines	SI	5	5	1	4
17	Builder intent is integrated into construction documents, and prefab opportunities are identified and published	DM	5	5	2	4
	Routinized Use Total		78	79	43	56
	Routinized Use Score		92%	93%	51%	66%
	Capability Competitiveness Score		100%	95%	35%	80%
	Effective Use (Use & Competitiveness =>75%)		Yes	Yes	No	No

ANALYSIS

The first author compiled and performed the simple calculations required. Without more data from other projects, no statistical analysis was possible. Proceeding, the authors focused on sense-making and application. Even during information gathering, it was apparent that the questions made sense and were not difficult to answer. This was true of the data; it produced insights that hadn't occurred to the second author. Similarly, the second author realized that the method and findings could be applied to future projects, making it easier for him to explain his approach and describe possible outcomes to project team members.

RESULTS

FINDINGS

All the process steps and resulting work routines contributed to Routinized Learning Capability. None were for Routinized Manufacturing Capability. Three of the 5 pathways were used on all 4 projects: Rational Calculation (classic product design problem-solving), Entrepreneurial Vision, and Knowledge Transfer. This was because the protagonist second author brought all three. The CID capability was used effectively on 2 of the 4 projects evaluated. In the other 2, the architect refused to collaborate on one, and the GC team members responsible for process steps did not execute them well enough on the other. In the 2 projects with Routinized Capability, the Constructable Design Development Documents within Allowable Cost subsystem was created to the benefit of the project. The General Contractor earned high success criteria scores and met their own competitive advantage goals.

The process steps were well conceived, including a very robust use of BIM, information sharing, and collaboration practices. And they could be taught to people willing to learn. Integrating the efforts of participating companies required their project leaders to commit to executing the process steps. While this was done by GC team members on all 4 projects, it succeeded on only 2 because other team members did not participate fully. Multi-Path System Emergence, Evolutionary Learning Capability, and Dual-Layer Problem-Solving were not visible on any of the 4 projects.

LIMITATIONS OF THE RESEARCH

The most significant limitation is that the CID capability was created without awareness of the Fujimoto framework, and the derivative research questions because the second author was not aware of them until he worked on this paper. Had it been otherwise, and Action Research been possible, participants and the researchers may well have learned and accomplished more.

Although Fujimoto speaks of routines, he only describes them at a high level. This is not surprising because that would require near constant attention from an informed manager or observer in the workplace. This is because routines are actions taken by people to execute their responsibilities. There could be just a few or many routines required to complete a process step by an individual or team. Even the second author could not recall and describe routines for action within the process steps. In the experience of the authors, designers and builders rarely define process steps, and even when this is done, transforming them into effective routines is left to individuals. This is why the primary element in this study is process steps. These did not include those for manufacturing, what Construction people think of as off and on-site production and assembly of building elements, so nothing was learned about this critical piece of the capability puzzle.

DISCUSSION

MEANING

Even though it is very different from current practice, CID capability can be created on this GC's projects where the second author is present. As with the 3 other capabilities studied in previous IGLC papers, the CID capability is fragile, meaning that it can be implemented where a protagonist can contribute vision, knowledge, and lead effective problem-solving, i.e., 3 of the 5 problem-solving paths. CID teams that fail to memorialize and communicate durations, the extent of BIM, and tracking progress are not as successful. New competencies such as Virtual Design and Construction and Design Management are required. The Project Superintendent must be involved earlier and to a greater extent than in current practice. Engaged project leadership and team alignment with design team customers is critical for success of CID capability. Cost and schedule metric tracking is yet to be defined and will require additional project team effort as well as greater rigor. The CID capability improved effective use substantially in 2 of the 4 projects, making it worthwhile to improve and implement whenever team members are willing to give it a try.

QUESTIONS THAT COULD NOT BE ANSWERED

How the CID process impacted the design team from their perspective is not addressed in this study. Similarly, the challenges faced by individuals implementing CID is not documented. The biggest question for the authors is how much better outcomes would be in an Action Research implementation with frequent team reflections and problem-solving focused on the process.

IMPLICATIONS

CID capability requires greater collaboration between team members. The fragmentation of design and construction is reflected within contractor organizations and is a barrier to implementing CID. Resources with deep construction knowledge are often not available, or are not encouraged to integrate early, both at the GC and the trade levels. Implementing CID requires people who are open to change and willing to learn, which is difficult without company and project cultures which support working in an integrated way.

CONCLUSION

KNOWLEDGE GAINED BY PARTICIPANTS, AND VALUE FOR PRACTITIONERS

It is both possible and desirable to create CID capability to provide greater value to the Owner. The design team must want early builder constructability input for the CID capability to impact the Constructable Design Development Documents within Allowable Cost subsystem. Without that, CID capability is wasted. Client contracting methods such as IPD and Design-Build are evolving and creating the opportunity for this process to occur. Builders and fabricators can create CID capability, which will extend its impact.

VALUE FOR PRACTITIONERS

The reluctance of the design team in the project where it was not successful was surprising. The traditional design process has been disrupted by the BIM process for years but has still not fundamentally changed how design is done and the cost of projects is predicted. The ability to connect design intent with builder execution is worthwhile because doing so eliminates waste and rework in design while making it possible for project teams to deliver significantly greater value to the customer.

RESEARCH INSIGHTS

The CID process challenges our current contracting method and the silos that exist within the AEC industry. Earlier procurement of trade partners and utilization of 3D collaborative environments make faster design iteration possible, leading to higher levels of cost and schedule certainty.

SPECULATIONS AND QUESTIONS

The authors' intuition is that integrated ecosystems composed of designers, builders and fabricators would want to develop CID capability, and at some point, make it a condition of entry. The capability to model cost at the space program level, studied in a 2020 IGLC paper (Berg et al. 2020) could and should be paired with CID capability. This would make it possible for integrated project teams to consistently capture cost and schedule impacts to feedback for clarification of design intent early in Conceptual Design. A big question is how CID capability can impact procurement and the supply chain to make outcomes more predictable.

FURTHER RESEARCH

Use Action Research to study another set of CID capability projects where the second author is engaged, and another where he is not, and the effort is led by other Design and VDC managers. Extend the CID capability to associate cost and schedule impacts of prefabrication opportunities that can be identified and memorialized earlier using the process. Capture and catalogue rules, constraints and assumptions made through the CID process to inform future projects with similar scopes.

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