THE EVALUATION OF ALTERNATIVE PRODUCTION SYSTEM DESIGNS WITH DISCRETE EVENT SIMULATION

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ABSTRACT

The business model of the building construction sector of the construction industry has changed very little over the years. The highly fragmented structure of the industry has led to an overwhelming focus on project management vice production control and has resulted in "artificial" constraints that limit the ways in which the physical product actually gets built. These artificial constraints render it difficult if not impossible to design the production system from a product-centric approach. The functionally-aligned traditional approach is characterized by four types of waste: (1) Duplicated direct and indirect overhead expenses generated by the numerous business entities involved in the construction, (2) Multiple mobilization/demobilization cycles, (3) Inability of subcontractors to organize their work as efficiently as they could if the other subcontractors were not in the picture, and (4) Rework to correct components that are damaged, disturbed or knocked out of alignment by others.

An alternative production system design is proposed, modeled on a parallel flow system used by Volvo in a final assembly plant in Uddevalla, Sweden. The advantage of this type of arrangement in accommodating variation is demonstrated with a simulation model of an idealized process. A research program is outlined which develops and evaluates with discrete event simulation similar type production system designs for selected building construction processes.

KEY WORDS

Production system design, simulation, parallel process

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INTRODUCTION

In general the business model of the building construction sector of the construction industry has changed very little over the years. It remains highly fragmented in both its organizational and functional structures, which has led to an overwhelming focus on project management vice production control. This misplaced emphasis on the tenets of project management fosters the fallacious argument that sub-optimization and minimization of costs of sub-processes will lead to an optimized project as a whole, produced at minimum cost. The widespread acceptance of the project management approach in construction is largely due to its proponents having a representational view of the world. There is a similar view in traditional operations management in manufacturing, which Johnston and Brennan call "management-by-planning" (Johnston and Brennan 1996). Practitioners of this approach view management activity as a sequence of the development, revision, and implementation of plans. The philosophy underpinning this orientation is the conception that everyday activities can be guided through the manipulation of representational models of the real world.

In a synergistic way, the evolution of the general business model in the industry has increased our adherence to and reliance on the project management approach and in some respects has trapped the industry in a mode that makes it difficult to move beyond the representational view of the world. The highly fragmented and functionally based organizational and contractual structures of the industry have resulted in "artificial" constraints that limit the ways in which the physical product actually gets built.

TRADITIONAL CONSTRUCTION MODEL

The production system utilized on a typical building construction project is structured around the aggregated unit of work generally referred to as an "activity." The various project activities represent the physical work or tasks that must be done to produce the project. These activities are then arranged in a certain sequence to define the planned flow of task accomplishment that will be followed to build the product. It should be quite evident that the actual process of defining the individual activities introduces artificial constraints that restrict the universe of possible production system designs. Since the entire building process from design on through construction is functionally structured, both from an organizational and contractual standpoint, tasks end up being aggregated into activities by trade classifications rather than by physical entity. Various activities are then functionally aggregated to higher-level groupings that represent work to be done by individual subcontractors. The production system is then designed around the imposed constraints reflected in the task composition of the individual activities and their subsequent grouping by subcontract. These artificial constraints render it difficult if not impossible to design the production system from a product-centric approach.

As a conceptual example of the traditional production approach, let's consider the construction of a typical interior partition wall in an office building. In the framework of the traditional project management approach, typically the work is decomposed into the following activities: the installation of the metal stud framework, rough-in of the electrical, communication, and control systems, rough-in of plumbing system, installation and finishing of drywall sheathing, painting/surface finishing of wall, finish electrical, and finish plumbing. The construction work proceeds according to the same decomposed organization. The drywall subcontractor first installs the metal stud framework, utilizing his labor and tools. Next, the electrical and plumbing subcontractors come onto the job to install their systems in the wall cavity between the planes that will be physically realized with the drywall sheathing. They drill and cut the metal studs as necessary to fit their systems into the wall utilizing their own complement of tools and equipment. Meanwhile, other building components, such as the HVAC ductwork and sprinkler systems are being installed in the same general area. These business entities are primarily concerned with optimizing their portion of the work. Temporal and space conflicts between them are generally resolved by the general contractor. Often, components already installed by others are disturbed, damaged or knocked out of alignment by these specialist contractors. Finally, towards the end of the project, after the damaged and disturbed components have been fixed, the final wall finishes are applied and the finish electrical and plumbing work is completed.

The above organization of work creates several wastes that ultimately must be paid for by the customer. First, the more separate business entities involved in the project, the more direct and indirect overhead must be borne by the project. Typically, each contractor will bring his own tools and equipment to the project. Much of this is duplicated by each contractor, i.e. multiple sets of interior scaffolding, work platforms and stepladders, numerous drills and other tools and equipment. Second, it is highly unlikely that all of the subcontractors will be able to mobilize/demobilize only once during the duration of the project. Generally, they will come and go from the project as dictated by the work available for them. The third type of waste is a direct result of the sub-optimization that each entity strives for in their individual processes. Because of the interference of other subcontractors, which have the same parochial interest in their own work, the individual subcontractor most likely will not be able to organize his work as efficiently as he could if the other subcontractors were not in the picture. For example, each contractor will seek to store his materials in the most advantageous location relative to his workface whether or not it impacts another contractor. He will install his permanent systems in specific locations in the work regardless of whether it is the optimum location from a whole project standpoint. The final major waste, which is closely related to the previous one, is the effort expended on a certain class of rework. Because of the opportunistic behavior of each subcontractor as he prosecutes his own work, other components of the work are occasionally damaged, disturbed or knocked out of alignment. At some point, these defects must be corrected with expenditure of additional labor and materials. This source of waste could not be better illustrated than with the following quote in a magazine dedicated to residential construction (Ruiz 2002).

> *I learned that my subs included a fudge factor in their bids to allow for mistakes…The framers anticipated returning to make repairs after the electricians, plumbers and sheet-metal trades were through hacking up the walls.*

The difficulties experienced with the traditional approach to production design in construction arise in part from man's inability to know the exact state of the world. This makes it impossible to adequately represent it in a model that can be reliably used to direct activity to bring the world to a desired state. The manifestation of this incomplete knowledge of nature is the existence of random variation in task and activity durations and the occurrence of unforeseen events on the project.

IS THERE A BETTER WAY?

The insidious effect of variation on processes is well known (Howell et al. 1993; Ballard and Howell 1998; Hopp and Spearman 2001). In general, two steps are taken to mollify its deleterious effects on processes. First, buffers are introduced between successive tasks in order to shield the downstream task from variation in the cycle time of the preceding task. Secondly, as the magnitude of the variation is reduced a corresponding reduction in the size of the buffer can be realized with an attendant reduction in the overall process cycle time.

It should be apparent that the effect of variation is highly correlated with the number of task handoffs and interdependencies inherent in a process. The traditional production system design used in construction today is highly conducive to the establishment of processes with numerous task handoffs and interdependencies that are very sensitive to the effects of variation. Therefore, a worthy objective of an alternative production system design would be the reduction in the number of task handoffs and interdependencies.

Another difficulty arising from the complexity of the traditional approach is the incapacity of the individual workers to become fully aware of the situation in which they are proceeding with purposeful action. In the terminology of lean production, there is an inherent lack of transparency of the production process. Another desirable objective, then, would be the increase in the transparency of the process to the individual workers.

AN EXAMPLE FROM AUTOMOBILE MANUFACTURING

In 1988, Volvo began assembling automobiles in a radically different plant in Uddevalla, Sweden. The assembly process, rather than being focused around a machine paced assembly line, was based on parallel flow production using long cycle time assembly work and included advance materials feeding techniques, holistic learning of the assembly work, and other innovations. (Engström et al.1998). The production process was divided into five separate assembly units of seven semi-autonomous work groups each with 8 to 10 workers per group. (Schuring 1996). Working simultaneously on three or four cars at a time, each assembly team completely assembled two to four cars each day. Each employee was required to master at least three of seven formally recognized skill sets. Because the cognitive process by which the assembly workers learn and remember the sequence and how to assemble a vehicle integrates manual skills and mental mapping, this type of manufacturing is commonly referred to as “reflective production.”

To further their understanding, these researchers studied the production at the Uddevalla plant with objective of comparing it to standard serial production. (Engström et al.1996) They observed the assembly workers to determine the time actually needed to complete various work tasks in the assembly of nine cars. These data were compared to standard assembly times that had been previously developed from time-and-motion studies on serial production lines. The vehicle with the longest standard assembly time only required 85% of this time to assemble. With the different standard assembly times for the nine vehicles normalized to the longest of them, the standard assembly times ranged from between 100% and 73%, with the actual assembly times ranging from between 90% and 67%. In every case, the actual assembly time was less than the standardized time. In addition, the mean work pace was 118% of that assumed in the time-and-motion studies. This increased pace was not due to more rapid movements, but by the manner in which the workers prepared to do the actual individual assembly tasks.

For example, they would generally bring more parts and tools within easy reach at the worker position than they would typically do on a workstation along an assembly line.

Lean and reflective production, which are similar, are both team-based philosophies. However, the lean teams do their work in accordance with strict standardized operating procedures with little freedom of execution. When a problem develops, the team cannot act in an ad hoc manner to resolve it and their only recourse is to report it up the chain. Learning is manifested by ever better standardized operating procedures.

In contrast, work groups in reflective production processes largely determine the manner in which they accomplish their work. The group reacts to problems by assessing them and formulating and implementing solutions without direct involvement of non-group members. Standard operating procedures are kept to a minimum with learning manifested by the group's ever increasing skill level to perform tasks and solve problems.

Schuring concludes that production processes characterized by large uncertainty in operational conditions or that have little repetition can only achieve operational autonomy with reflective production. Simply put, it would be extremely difficult or impossible to establish a standardized operating procedure to cover every eventuality of such a process.

A THEORETICAL EXAMPLE

The main technical difference between traditional lean production characterized by serial processes and reflective production in parallel processes is in the manner in which they deal with the variation in task cycle time (Engström et al.1996). As previously discussed, in serial processes in which tasks are tightly coupled to each other, the efficiency of the whole process is sensitive variation. Lean manufacturing has as its objective the reduction of task cycle time variation by utilizing standardized work procedures, reliable equipment, and high-precision components. In situations in which the variation cannot be satisfactorily reduced, task coupling is reduced by the introduction of buffers between successive tasks. In contrast, reflective manufacturing, rather than striving for the reduction of variation, accommodates it by using parallel, independent production flows.

As a simple illustration of the ability of a parallel arrangement of tasks to accommodate variation, an idealized operation consisting of four consecutive tasks was modeled in EZStrobe. (EZStrobe is a general-purpose simulation program designed for modeling construction operations. (Martinez 2001)). This operation does work on a "part" at each of four consecutive workstations as it flows from the input to the output of the process. One individual works on each part at each workstation. In the traditional serial arrangement of tasks, workers are assigned to do a specific task at a specific workstation. In the first model, diagrammed in Figure 1, one worker is assigned to each workstation. A part enters the process and is worked on at workstation 1 by an individual. It is then moved to a buffer until the worker at workstation 2 is available to work on it. The part moves in a similar manner through workstations 3 and 4 until it is output from the process when the work has been completed at workstation 4. There are 500 parts to be processed. To simplify the model, the average duration of a part at each workstation was assumed to be 5 minutes. The operation was simulated at three levels of task variability: none, moderate and high. A specific task duration at a workstation is assumed to be modeled as random variable drawn from a symmetric PERT distribution. The parameters of the PERT distributions for the three levels of variability are summarized in Table 1. The simulation was run 1000 times at each level of variation to obtain the average and standard deviation of the total process time and the average capacity utilization of the workers.

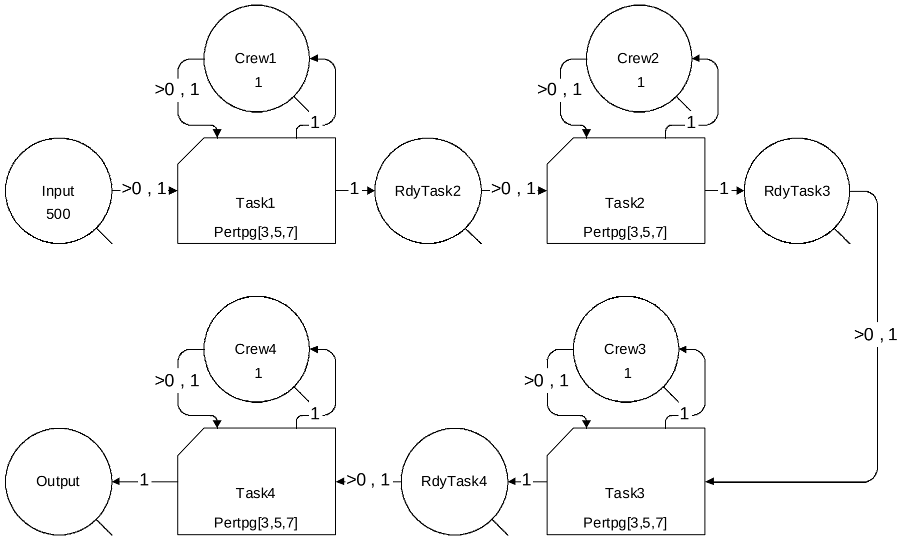

Figure 1: Serial Process.

Table 1: Distribution parameters of task durations.

Level of Variability of Task Duration	Task Duration, minutes		
	Optimistic	Most Likely	Pessimistic
None	5	5	5
Moderate	3	5	7
High	1	5	9

The process arrangement was then changed to a parallel configuration. The EZStrobe model of the parallel arrangement is shown in Figure 2. In this arrangement, the same number of workers is used in the process and the task durations at each workstation are represented by the same PERT distributions as used in the serial configuration. Again, the simulation was run 1000 times at each level of variation.

As seen in Table 2, which compares the total process times from the different simulation runs, the parallel configuration is better able to accommodate task variation. The average total duration increases less than 1% from 2500 minutes to 2513 minutes as the task variation increases. This is compared to a more than a 5% increase in the total duration with the serial process configuration. In addition, the variation in the process duration, as reflected by the standard deviations, is greater for the serial design.

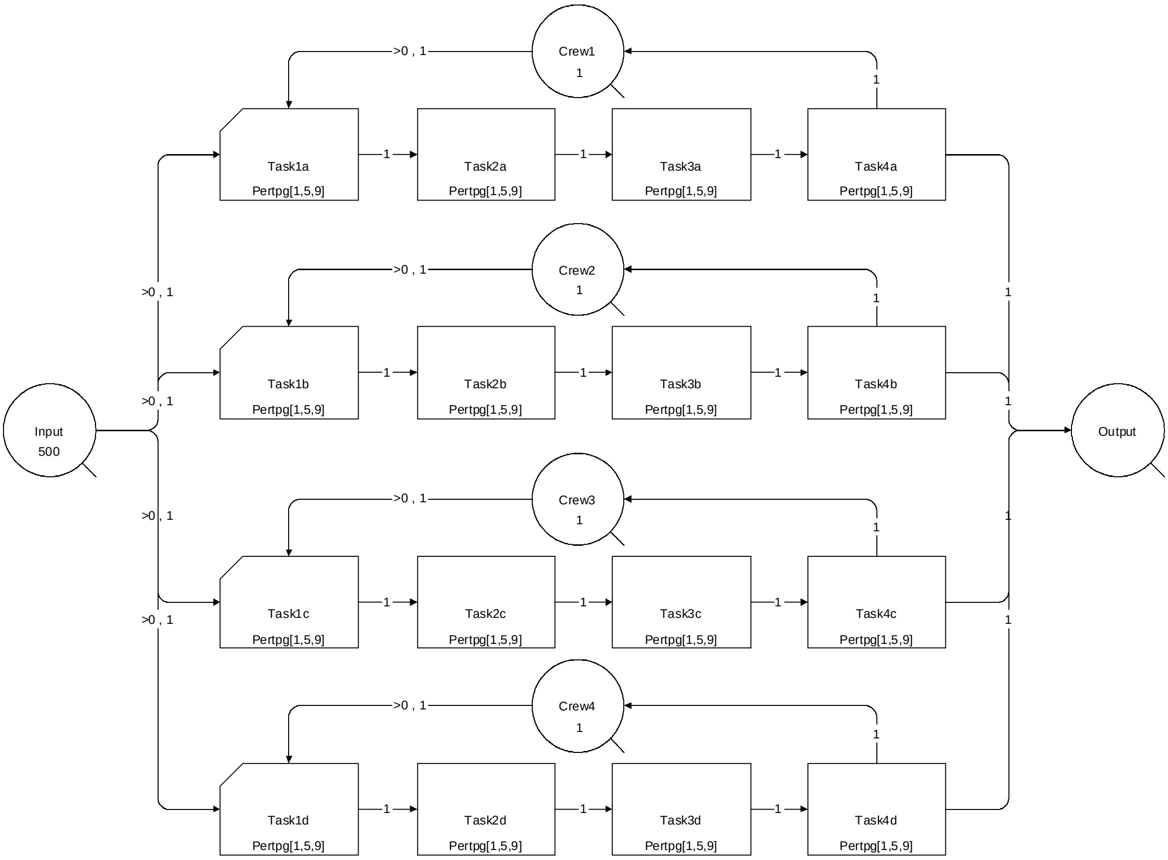

Figure 2: Parallel Process.

Table 2: Total process time.

Configuration	No Variation		Moderate Variation		High Variation	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Serial	2515	0	2582	20.7	2652	41.3
Parallel	2500	0	2507	13.8	2513	26.7

Similarly, the capacity utilization of the workers in the parallel process configuration is greater than 99% at all three levels of variation. However, capacity utilization of the workers in the serial layout decreases from more than 99% in the case of no variation to approximately 94.5% at the high level of variation. Capacity utilization results are presented in Table 3.

Table 3: Capacity Utilization of Workers.

Configuration	Variation		
	None	Moderate	High
Serial	99.4%	96.8%	94.4%
Parallel	100%	99.7%	99.7%

However, the greater efficiency of the parallel process design does come at a cost. Rather than having one set of tools and equipment for each workstation, we now need four complete sets. In addition, each worker must be trained and skilled in four tasks rather than one. But this simple example shows that from a labor productivity viewpoint, as variation within the process increases, the greater the benefit of utilizing a parallel layout.

Taking this example one step further, let's assume that the work done in the traditional manner (serial configuration) is performed by four individual subcontractors, one assigned to each workstation. It is reasonable to believe that each is primarily interested in accomplishing their part of the work in the most efficient manner possible. It is unlikely that they would be willing to reduce their productivity (without compensation) in order to increase the overall productivity of the entire process. Therefore, they will not mobilize their workers until sufficient backlog has built up in front of their workstation such that they can work without exhausting the input queue. Unlike an established machine-paced industrial assembly line, a typical construction process on a specific job does not have a complete history until it has entirely finished. Therefore, the succeeding subcontractor generally will come onto the job at some arbitrary buffer level that has built up from the output of the previous subcontractor rather than a at the precise point that would, on the average, keep his crew working at full capacity utilization. Although these buffers do not reduce labor productivity, they serve to increase the total duration of the process, with attendant wastes of increased work-in-process and indirect and overhead expenses.

PRODUCTION ENVIRONMENT IN BUILDING CONSTRUCTION

The lean production system is a distillation of the philosophy and techniques perfected by the Toyota Motor Company during their quest to successfully compete with the mass production based automobile manufacturing prevalent at that time. Three dimensions can characterize the manufacturing environment in which the lean production system was developed and has been overwhelmingly successful.

- Complexity – In terms of numbers of trades and subcontractors involved in the final assembly of the product and the number of handoffs and spatial conflicts between them, manufacturing is of low complexity.
- Uncertainty – Product design is fully detailed such that nothing is left to the discretion of the assembler. Others have previously decided the location, size, and torque specifications for every single screw or bolt. Standard procedures and sequences have been established for the accomplishment of every task. The automatic movement of the assembly line paces the rate at which the

work is done. Incorporated materials and equipment are fully specified in terms of size and mounting provisions.

- Sequencing – The sequence in which the individual parts and components are assembled to produce the final product is well defined and extremely rigid.

Also, it is important to keep in mind that the repetitious nature of manufacturing production permits one to gain knowledge about the process and the opportunity to act upon that knowledge to optimize the process.

In contrast, construction production, especially in the building construction sector, can generally be characterized by its "once through" nature, providing little opportunity to gain knowledge of the process and the subsequent optimization. In addition, in terms of the three characteristic dimensions described above, construction is diametrically opposite of manufacturing:

- Complexity – Numerous trades and subcontractors are involved in the final assembly of the building. The tasks and processes are closely coupled with many handoffs, requiring close coordination between them. Space is a valuable resource that must be allocated in a rational manner.
- Uncertainty – The final design documents are schematic in nature for many of the incorporated assemblies and components. Size and mounting provisions of much material and equipment are not known in advance of installation. The craftsman in the field determines exact location, method of installation and manner of attaching many components to the structure.
- Sequencing – No hard and fast detailed sequence of construction is pre-established. A general sequence defined by the physical constraints of the thing being built (i.e. foundation before frame, etc.) and other prerogatives is recognized. However, even in those situations in which highly detailed planning documents are developed, there is wide latitude in the exact sequencing of the innumerable tasks involved.

ALTERNATIVE PRODUCTION SYSTEM DESIGNS

As was shown in the Volvo's Uddevalla assembly plant, a parallel production system, in which final assembly of entire automobiles was done by a small group of multi-skilled workers, proved to be an efficient method in a manufacturing environment. The question, then, is will a similar type parallel design within the complex, uncertain and soft sequencing domain of building construction have a potential to yield analogous results for selected construction processes.

To test the above ideas a research plan has been developed to examine the hypothesis that current production system design can be improved by removing the artificial constraints imposed by the traditional craft division of labor and the correlative organizational structure and the subsequent restructuring of it in a parallel-type arrangement in accordance with the principles and theory of lean production.

Improvement, in the context of this research, will be evaluated using lean metrics such as degree of waste, cycle time, and amount of work in process. These manufacturing derived metrics will be modified as necessary to fit into a project-type environment, i.e. cycle time is equivalent to the time it takes to complete a certain set of sequential tasks on the construction project.

RESEARCH METHODOLOGY

The construction domain of interest in which to test the hypothesis, which is characterized in terms of the above described dimensions, is the interior fit-out of typical commercial office space. The construction of interior partitions and ceiling areas involves the installation of numerous specialized systems and requires the close coordination of many disparate trades. Ideally, one would next modify these operations to test alternative production system designs. The realigned operations would then be studied and compared and contrasted with the baseline cases. Since the testing of the hypothesis would be expensive and risky to do on actual processes, discrete event simulation will be used to test alternatives and reveal the opportunities and limits of lean production theory and principles in this most challenging environment.

It is thought that the “atmosphere” in which work is being done will influence the degree to which the application of lean theory and principles in the form of alternative production system designs will improve the performance of the project. Ideally, three similar projects will be studied, each at a different location on the continuum of “in control-ness.” This latter dimension attempts to establish the degree to which the project managers are ahead of the situation and have reduced the uncertainty. The value of the metric is inversely manifested by the amount of decision-making and problem solving done at the workface rather than removed from it. For example, a project in tight control would have its material precut, packaged into task specific kits and delivered to the workface bundled by assignment. A project in lesser control would have material delivered precut and bundled by size or type, but not packaged into kits. A project under minimal control would be manifested by the delivery of uncut raw materials to the workface. It is believed that the more that the project is in control the less will be the improvement obtained by implementing an alternative production system design.

The research methodology is a two-phased approach. The objective of the first phase is to define a baseline production system design that represents the traditional manner of work accomplishment. This baseline will establish the reference point against which alternative designs will be measured. The baseline models will be developed from observations of the three types of projects discussed in the previous paragraph. The manner in which the tasks are done will be documented in great detail, along with information providing specific details on the production system. The data collection will be done such that conceptual models and subsequent simulation models can be developed. The deliverable from the first phase of the research will be a verified and validated discrete event simulation model that is an adequate representation of the real situations observed in the field.

Phase II is the experimental portion of the research. The baseline conceptual and simulation models will be modified to test alternative production system designs that will be developed within a lean production framework. Output from the alternative simulation models will be analyzed for performance measures of interest using the baseline output as the reference point.

CONCLUSIONS

It is apparent that the construction industry has not progressed as fast in adopting the new philosophies and techniques that have become a competitive necessity in the manufacturing sector. It is thought that absent the “artificial” constraints imposed by the fragmented business model and the division of labor along rigid craft lines, alternative production systems can be designed that provide an improvement over the status quo. These production systems, rather than being designed around the needs of the involved organizations, are structured, in keeping with a lean philosophy, around the needs of the product. The described research program will reveal the potential opportunities afforded by this approach to production system design. However, future research, in which the alternative designs are tested on actual construction processes, will be needed to truly validate the hypothesis.

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