Decision Support Methodology for Prefabrication Decisions on Green Building Projects

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Abstract: The growing interest in sustainable construction, technological improvements, and increasing labor costs provide opportunities for prefabrication strategies to enhance 'green' or 'sustainable' building projects. In such projects, choosing the appropriate prefabrication strategy under variable project conditions becomes important to achieving outcomes that help meet green building goals, such as reduced material use and improved energy efficiency. Subsequently, decisions about prefabrication should be carefully coordinated with a series of tactics throughout the team selection, design, procurement, manufacturing, and construction stages of a project. The goal of this paper is to help project teams take full advantage of potential prefabrication opportunities and determine appropriate strategies across different building systems in order to better achieve overall project goals regarding initial cost, schedule, quality, and sustainability.

Existing decision-making tools for prefabrication are limited and typically focused on construction decisions. Building upon the existing concept selection optimization techniques, a decision-making framework is proposed in this paper. It allows project teams to examine opportunities existing in the whole delivery process of a building system, compare different options (e.g. subcontractors & material suppliers, procurement methods, designs, construction methods, etc.), and make effective prefabrication decisions through understanding the synergies and tensions among prefabrication strategies, building processes, and building performance early in the design phase. A value-based dynamic programming tool is presented and its application on an actual case study projet is described. Conclusions regarding the use of this tool, and the potential value of prefabrication strategies on sustainable projects are provided.

Keywords: Decision-making, Green Projects, Prefabrication Opportunities, Strategies, Tactics

1. Introduction

'Green' or 'sustainable' buildings are those in which efforts are made to minimize resource consumption and maximize energy efficiency and the health of occupants. These facilities are considered to have health and productivity benefits for occupants and have increased in demand by both public and private owners. In the U.S., these facilities are also considered to be more challenging to design, and are often associated with cost premiums. The efficient delivery of green buildings is thus an important question facing both academia and the architecture, engineering, and construction (AEC) industry.

One strategy worthy of exploration is reducing construction costs by improved production and reduced waste, and using the savings to offset the costs of some high performance building components. Prefabrication, preassembly, and modularization have been successfully employed in the manufacturing industry (especially in the highly competitive automotive and aerospace sectors) as an application of *Lean Production Principles* that aim to streamline production of systems and reduce waste. A disconnect exists, however, between the commonly perceived benefits of prefabrication and the outcomes that are valued on green building projects, such as reduced material use, recycling of materials, improved quality, and reduced construction time. The terms prefabrication, preassembly, and modularization are often interchanged in practice, and not well defined. In this research the term "prefabrication strategies" refers to the "single or combined use of prefabrication, preassembly, and modularization on site or at a location other than at the final installation location."

2. Objective

This paper presents the latest findings from on-going research examining a prefabrication strategy selection methodology (PSSM) for building systems. While intending to be universal in application the research focuses specifically upon curtain wall systems, mechanical systems, and wall frame systems. Derived from the existing techniques for concept selection in product design, the methodology used helps project teams examine how the system-level prefabrication strategies can be achieved by a series of tactics (i.e. approaches) at different project stages (e.g. team selection, design, procurement, manufacturing, and construction) and how the selection of these strategies can contribute or detract from project goals through evaluating the interplay between prefab-related tactics, building processes, and building performance.

3. Opportunities and Benefits of Prefabrication

Although widely used for over a century in construction, prefabrication strategies are still considered by many industrial professionals as merely an approach to reduce labor costs. Viewed with more scrutiny, prefabrication strategies have vastly more to offer in terms of reducing construction time and first cost, improving quality, and helping achieve the sustainability objectives for a project. Potential benefits associated with these four opportunity areas are further explored and summarized in Table 1.

The conditions in the building industry are far more complex than the manufacturing industry due to the fact that every building project has a unique location, design requirements and priorities. Therefore if not employed appropriately, prefabrication strategies can also result in negative impacts to projects such as change orders, coordination problems, long lead times, and poor quality due to inappropriate dimensional tolerances.

Table 1: Potential Benefits of Prefabrication Strategies

	1st Cost (Budget)	Time (Scheduling)	Quality	Sustainability
Potential Benefit Areas	Reduced material waste and increased material recycling	Preconstruction speed (e.g. design, planning, and procurement)	Customer requirements (e.g. aesthetics, expected functions, and life-span)	Health and safety during construction
	Direct labor (i.e. field workers) savings	Manufacturing & delivery speed	Design/Engineering tolerances	Improved occupant health
	Indirect labor (e.g. field overhead) savings	Increased speed of construction on-site	Streamlined information flow & management processes through design, manufacturing, and construction	Economic development in local communities
				Material reuse and/or recycling
	Design speed			Flexibility/adaptability
	Equipment requirements			Reduced operation & maintenance requirements
	Reduced rework			
	Reduced transportation			

4. Background

4.1 Current Decision-making Tools for the Use of PPMOF

Systematic analysis and decision-making is the key to successful implementation of prefabrication strategies. Two existing tools, the PPMOF (Prefabrication, Preassembly, Modularization, and Off-site Fabrication) decision framework by CII (Construction Industry Institute) and the IMPPREST (Interactive Method for Measuring PRE-assembly and STandardisation benefit in construction) toolkit developed at Loughborough University in the UK are the most important. Both of these tools contain a preliminary decision guide followed by a quantitative analysis. The first part is based on very basic project information such as schedule, site attributes, availability of local labor and suppliers, etc., whereas the latter part usually asks for more specific details (e.g., material cost, labor cost, equipment type, etc.) to increase the accuracy of its results. Both tools are available in either paper form or computer-based version. IMMPREST considers PPMOF as a whole and uses the term "Standardization and Preassembly" (S&P), while the PPMOF framework enables the users to further perform tactical analysis of PPMOF alternatives. A notable feature of IMMPREST is that it brings "softer issues" such as health and safety, sustainability, and effects on management and process into the decision-making of S&P and explicitly defines the ways to measure since its researchers argued that "monetary measures are inadequate for items that cannot be directly attributable to an element" (Blismas, et al, 2006). While both conceptual frameworks intend to facilitate a more systematic thought process and hopefully better decisions, some embedded limitations make them less likely to be widely accepted by the industry. The major drawbacks include:

- **Ambiguous definition of work processes:** The terms prefabrication, pre-assembly, and modularization are not explicit. According to CII's (Construction Industry Institute) definition (CII, 2002), prefabrication is often focused on components which involve the work of a single craft, while preassembly is generally used on a system, and modularization includes portions of many systems and essentially refer to increasing levels of prefabrication work with modularization at the highest level. In practice, actual work strategies involve combinations of prefabrication and pre-assembly. One of the primary features of these strategies: the location the work takes place, is also missing from these definitions, e.g., factory, off-site, or on-site.

- **Lack of practicability in intended functions:** The goals of the existing tools are either too general or too specific. The tool PPMOF developed by CII aims to identify one strategy as the best solution for a project but its value is blurred by the fact that these strategies are always mixed together during their practices and it is ambiguous how to make clear distinctions between them. The IMMPREST tool by Loughborough University in the UK intends to facilitate the evaluation of benefits from use of "standardization and preassembly" as a project-wide strategy, but it still relies heavily on the decision-maker for issues such as where and how to implement strategies. To ensure the successful implementation of prefabrication strategies, a series of decisions need to be made during design, supply chain management, manufacturing, and construction. Therefore further assistance on identifying the PPMOF opportunities in these stages can be very helpful to a project team.
- **Scope limitations:** Another common shortcoming of these tools lies in their quantitative analysis section, which requires very specific details (e.g., material cost, labor cost, construction equipment type, etc.), whereas such information is typically unavailable at early stages of a project and the situation can be even worse for design-build projects due to their nature. Undefined or poorly-defined designs only make it difficult to utilize these tools and may even mislead the final solution. The IMMPREST project team found out that "many of the items listed were not currently recorded in any meaningful way" in a follow-up survey, which was why the toolkit, especially the in-depth part was not so well accepted (Pasquire et al., 2005).
- **Lacking a comprehensive perspective of PPMOF benefits:** Neither of these tools fully considers the needs of sustainable building projects and even though IMMPREST does include some of the soft issues in its evaluation, the users still cannot tell how the value-set on these projects may influence the selection of prefabrication strategies. To address this issue, more descriptive and comprehensive sustainability criteria and the potential sustainable benefits of prefabrication strategies need to be clearly defined.

4.2 Available Decision-making Techniques in Concept Selection

The purpose of the proposed PSSM is to help a project team find a 'best-fit' prefabrication strategy for a building system. The term 'prefabrication strategy' here denotes a system-wide plan which involves many decisions in every stage. More specifically, it means the path of selecting which prefabrication opportunities to take advantage of and what tactics to use throughout each stage of a project. Different prefabrication strategies indicate different combinations of such opportunities and tactics. The research problem is considered as a multi-stage decision-making problem. Decision-makers need to evaluate a series of inter-woven prefab-related opportunities and associated tactics across different stages and try to determine a combination that benefits a project the most within given constraints and available resources. The methodology therefore should allow the team to consider all possible combinations and eliminate infeasible or suboptimal options with quantified measures.

Being aware of the limitations embedded in the traditional decision-making process for prefabrication strategy selection and the related tools, applicable technical resources were sought from engineering design, industrial engineering, manufacturing, and architecture. A number of widely used decision-making techniques for concept weighting and selection have been reviewed, such as SMART (Simple Multi-Attribute Rating Technique) (Schultz et al., 1998), QFD (Quality Function Deployment) Matrix (also known as “House of Quality”) (Sullivan, 1986), AHP (Analytic Hierarchy Process) (Saaty, 1990, March et al., 1993), etc. Although adjustments still need to be made to suit the specific needs in this research, two multi-stage decision-making approaches: the CSM methodology and dynamic programming provide valuable insights and bring great potential into this study.

The CSM Methodology

In the selection of building systems, many trade-offs exist that can complicate the choice of design and construction strategies. For example, in the case of a curtain wall system, it is highly advantageous to assemble building skin components in a factory environment to maintain good quality, reduce material waste and minimize potentially dangerous construction activities on a building perimeter. However, the shipping and logistics of larger prefabricated components can present many on-site challenges and costs. The evaluation of concepts with such trade-offs can be difficult to perform. In addition, design teams often lack knowledge of all potential benefits and trade-offs associated with prefabrication practices used by different building trades. King and Sivaloganathan (1999) proposed a new methodology for concept selection. The functions are very similar to QFD however a quantified measure is used to evaluate coupled decisions. The structure consists of two parts (see Figure 1). One is a compatibility chart, where numerical scores are assigned between every two concepts (see Table 2). A typical concept vs. function chart in which scores are given based upon how each concept fulfils each function is also provided. The overall score of each configuration equals the summation of concept-function scores multiplied by the product of compatibility scores. A macro is used at the end of the process to perform and order the calculations since the number of possible configurations is typically extensive.

The methodology intends to facilitate more complicated decisions; however, the computations used here are not exhaustive, which means the final decision is based on results from only some of the possible combinations. In addition, when a large number of concepts and/or criteria are involved, the matrices grow bigger and more complex, and the procedure becomes lengthy and cumbersome. These limitations can be overcome however, providing a well-defined structure of decisions and options are identified, and choices are limited to a realistic number of considerations that can be understood by a user of the tool.

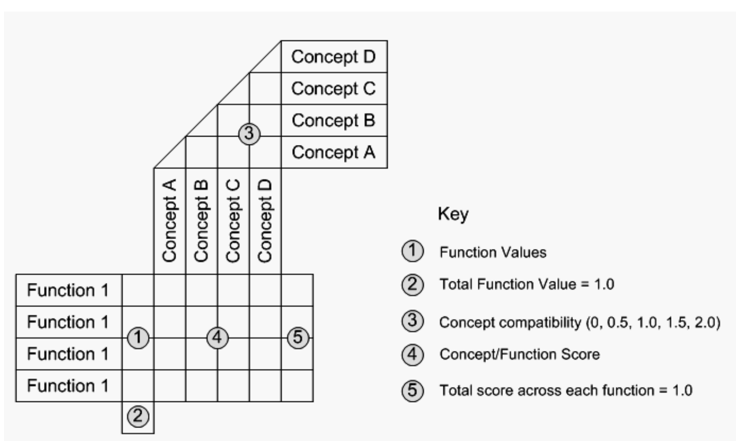

Fig. 1. Function-concept matrix showing relationships exist between potential concepts (Source: King & Sivaloganathan, 1999)

Table 2: Concept compatibility scores (part 3 in Figure 1) assigned between two concepts (Source: King & Sivaloganathan, 1999)

Score	Meaning
0	Mutually exclusive concepts that cannot be combined
0.5	Difficult to have concepts together, but possible
1.0	No effect on concepts if both are chosen
1.5	Good combination of concepts that work together
2.0	Excellent combination, the concepts reinforce each other

One goal of this research has been to define a set of functions and concepts that can be applied across variable types of building systems and permit the use of a usable yet comprehensive concept-selection approach by project teams.

Dynamic Programming

The concept of dynamic programming (DP) was first introduced by Bellman (1957) as a tool to solve many complex optimization problems involving a sequence of interrelated decisions, such as network problems, scheduling problems, allocation problems, etc. Figure 2 illustrates a very common application of DP called the "shortest path" problem, where the ultimate goal is to identify the shortest path that connects nodes from stage I to stage V knowing the distance between every two nodes at two consecutive stages. An important feature of DP is that it allows decision-makers to consider every possible combination during concept selection to achieve the 'real' optimality. Software such as WinQSB's dynamic programming module is available to perform the extensive calculations.

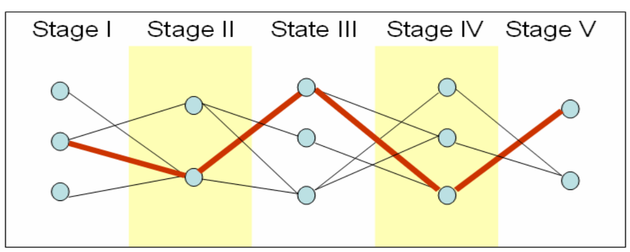

Fig. 2. Shortest Path Problems

5. Proposed Decision-Making Process & Framework

To achieve the goal of this research, a holistic view of the overall decision-making process needs to be established. A building system therefore was examined first at the stage-level. The following five stages: *Team Selection (TS)*, *Design (DS)*, *Procurement (PRO)*, *Manufacturing (MFG)*, and *Construction (CON)* were identified according to the way a system was typically produced and installed.

The investigator then conducted preliminary interviews with experienced trade contractors that were involved in this research. The main goal of these interviews was to collect the critical prefab-related decisions they typically made during the five stages to ensure a successful delivery of these building systems. Despite the distinguishing features of system types, decisions that could help bring out more value of prefabrication strategies were further categorized into 14 general areas, also called "*opportunities*" (annotated by stage as Team Selection: TS-i, Design: DS-i, Procurement: PRO-i, Manufacturing: MFG-i, and Construction: CON-i, where i = 1, 2…n opportunities). Assuming value is created when process or product waste is reduced and/or quality is increased, the criterion used for identifying these opportunities is defined as: "any potential value-added process or attribute that is enabled by increasing the scope of prefabrication strategies during design, procurement, manufacturing, and construction". Also based on the interview results, a set of potential "*tactics*" (annotated by stage as Team Selection: TS-ij, Design: DS-ij, Procurement: PRO-ij, Manufacturing: MFG-ij, and Construction: CON-ij, where i = 1, 2…n, j = a, b, c…) in each stage and for each opportunity were predefined. For example, "*TS-2: Subcontractor Selection*" is one opportunity area in *Team Selection*, whereas "*TS-2a: Design-Build Subcontractor*" and *"TS-2b: Subcontractor without in-house design capability"* are considered as two potential tactics in this area. One is not necessarily always better than the other since project conditions and available resources may vary.

Figure 3 below shows the relationship between stages, prefabrication opportunities, and their tactics. This research problem can be viewed as a shortest path problem in DP with the exception that the goal is to maximize utilities instead of minimizing costs. The following rules apply in order to make use of the CSM methodology and DP:

a) The tactics for each opportunity should be discrete.
b) At most one tactic will be selected for each opportunity.
c) Tactics are selected based on their overall contribution to the original project goals regarding initial cost, schedule, quality, and sustainability. Therefore, making good decisions here requires a decision-maker to maximize the combined value of tactics he/she selects for each opportunity.

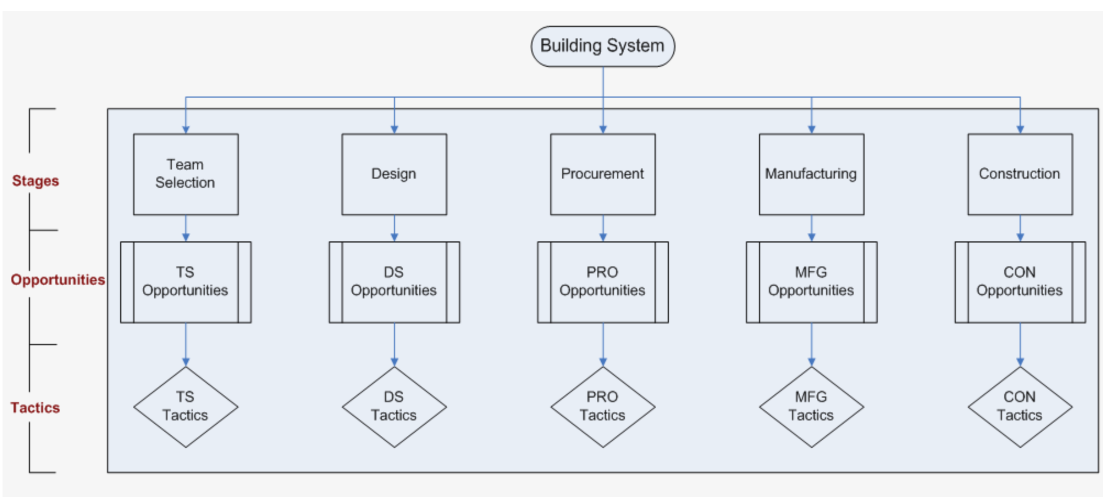

Fig. 3. Stages, Prefabrication Opportunities, and Associated Tactics

This approach allows the effect each tactic has on others throughout the five stages to be assessed and to measure this effect at a summary level, providing a more quantitative analysis in the overall decision-making process. A value table is used to prioritize project goals so weights can be taken into account to evaluate the impact tactics on the project.

Due to the fact that these tactics are not always complementary, their interrelationship will be assessed in the compatibility matrix. A similar compatibility scoring structure from the CSM methodology will be used in which alternative pairings are assigned a numerical value depending on their level of compatibility (Figure 4). For instance, “having an integrated design environment (e.g. a design-build project team)” does not affect “the availability of local skilled labor” (“design-build” is an alterative in the design stage and “labor availability” is an alternative in the construction stage). Therefore the compatibility of these two alternatives can be given a score of 1, meaning there is no compatibility tension.

By considering the individual project-wide impact of each tactic and the interrelation among all potential tactics, an “optimized” combination of tactics can be derived which suggests the best-fit prefabrication strategy for a building system for that project. The dynamic programming is used here to calculate the overall value of every tactic combination. The one with the highest value is identified as the optimum solution to the case being analyzed.

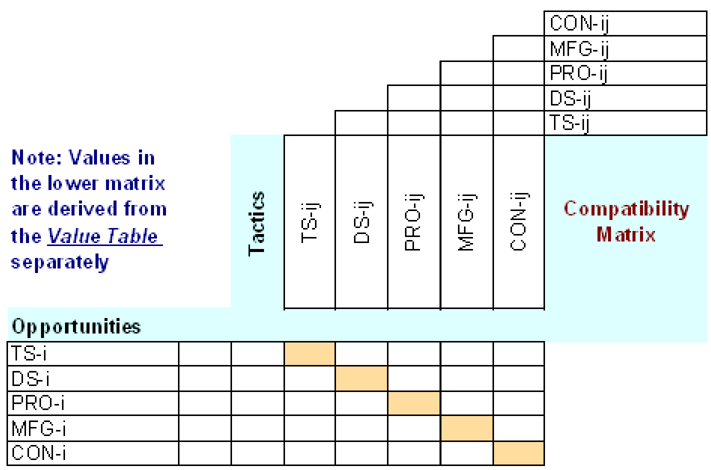

Fig. 4. PSSM Analytical Matrices

6. Pilot Case Study: The Early Childhood Learning Center (ECLC)

The proposed PSSM is applied to the roof system on a 4000 SF childcare facility: the Early Childhood Learning Center (ECLC) for illustrative purposes. This project was built in the summer of 2005 for Chief Dull Knife College in Lame Deer, Montana and was mostly designed and constructed (except for sitework, foundations and MEP work) by a group of volunteer students and faculty from Penn State University, University of Washington, and University of Wisconsin. A LEED certified green building was pursued, therefore green materials and sustainable technologies were employed which included an SIP (Structural Insulated Panel) roof frame, a mix of SIP and strawbale wall systems, radiant floor heating, evaporative cooling, CO2 monitoring, and digital climate control. A unique feature about this project was its “blitz-built” environment. The superstructure of the ECLC had to be completed in three weeks by a group of unskilled or semi-skilled volunteers. Hence “the use of prefabrication strategies to achieve the compressed schedule must be carefully balanced with the desires to maximize volunteer labor” (Luo, Riley, Horman, 2005).
Two types of roof panels were considered during the early phase of design.

Option 1: R-Control SIPs: An R-Control SIP consists of a Perform Guard Expanded Polystyrene (EPS) insulation core and OSB skins. The typical weight is about 3-4 psf. Panels are provided by a local manufacturer and are available in variable sizes which can be erected onsite either manually or by mechanical equipment such as a crane. Prep-work is needed before installation. The project team had worked with this manufacturer several times before on its previous projects and had a good relationship

Option 2: Agriboard Panels: Agriboard is made from compressed wheat or rice straw with exterior skins of straw-based OSB and structural support of laminated strand lumber (Agriboard Industries, 2006). These panels weigh about 14 psf (for 7-7/8" panels) (Agriboard Industries, 2006) and thus a crane is often required in the field. The panels are produced out-of-state which increases the material cost, however, since they arrive ready for installation with minimal prep work, a smaller crew is needed.

The following are the three possible prefabrication options for the roof panel erection:

1. Preassemble and erect R-Control SIPs onsite by hand;
2. Preassemble R-Control SIPs onsite and erect them with a crane;
3. Install Agriboard panels with a crane.

To maximize the value of these options, there are some other decisions to be made, such as "should the team stay with someone they know of", "at which stages of the project and system design should the subcontractor/manufacturer get involved", "what panel size should we choose", "who will provide the crane if needed", etc. The potential solutions to each question are considered as "tactics" and in many cases they are interrelated, contributing or detracting from one another. These potential system-level prefab-related tactics along with the overall project goals will be defined, assessed and analyzed by the project director and the research investigator using the proposed PSSM. The results should be able to identify the best combination of tactics for the given project conditions, which implies a good balance among work flows, labor use, construction costs, quality, and sustainability objectives.

7. Discussion and Conclusions

Prefabrication strategies can result in many outcomes that are synergistic with the goals and values pursued on green projects. A disconnect exists between these potential benefits and the typical process used to select prefabrication strategies. This paper presents a methodology to account for a comprehensive and thorough set of opportunities that exist through team selection, design, procurement, and construction phases of building projects. A dynamic programming methodology is applied to assist with the identification of a "best fit" approach for a given system. In a simple case of a roof panel system selection, the complex interaction between variable types of prefabrication approaches is illuminated.

Prefabrication strategies require time and extensive system knowledge. Some decisions need to be made early even before the design starts such as determining the appropriate procurement method and selecting the right team, which can have a tremendous impact on many other decisions later on. Without an effective tool to identify available prefab-related tactics and judge their values rationally, it is hard for project teams to quickly select the strategies that will bring the best outcomes under specific circumstances solely based on their past experience.

Case study research is currently in progress to identify patterns of interactions between prefabrication strategies across variable types of building systems. Additional research on how to best utilize prefabrication to achieve sustainable goals is needed. The key variables that dominate the decision-making process and the attributes of building systems which can most benefit from prefabrication strategies must be identified. Meanwhile, to ensure the results can be generalized across systems, multiple and diverse building systems must be tested.

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