Considering Prework on Industrial Projects

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Abstract: Prefabrication, preassembly, modularization, and off-site fabrication, collectively termed as prework have become more viable with recent advances in design and information technologies. These construction methods offer a substantial opportunity to improve project performance when circumstances merit. Successful implementation of these methods on a particular project requires systematic analysis and early decision making based on specific factors of the project. This paper identifies those factors influencing decisions on the use of prework, and current industry practices for evaluating the applicability of prework on industrial projects. It then presents a decision framework to assist industry practitioners with evaluating the applicability of prework on their project, and describes a computerized tool to aid project teams in the decision-making process. The developed framework and tool are useful and effective in the decision-making process, and easy to use, as validated by practitioners in the industry.

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Introduction

Owners demand high levels of value, safety, quality, productivity, and performance in their capital projects for their competitiveness and profitability. In addition, both owners and constructors face a current and projected shortage of skilled labor (BRT 1997). Prefabrication, preassembly, modularization, and off-site fabrication, collectively termed as prework (PPMOF) can help overcome such project challenges and, properly used, offer a substantial opportunity for improved project performance. On the other hand, the use of PPMOF can also bring about many changes in projects and place new demands or complexity on project organization, engineering, procurement, planning, monitoring, coordination, communication, and transportation (Tatum et al. 1987). Concurrently, flexibility regarding design change decreases.

Prework has become more viable in recent decades given advances in design and information technologies, while key factors influencing decisions regarding the use of PPMOF have changed. A previous research effort found that the use of prefabrication and preassembly in the industrial sector has almost doubled over the preceding fifteen years (Haas et al. 2000). Yet, the industry in general has not fully recognized the potential for project improvements from the use of PPMOF. This has been primarily the result of a lack of awareness of the impacts and a tendency to postpone early decisions on the applicability of PPMOF, which can preclude their use.

Relevance to Industry Practitioners

Given the challenges faced by the industry coupled with the impact of recent revolutionary technological advances, a clear need emerges for a decision-making framework that encompasses all factors driving or impeding implementation of PPMOF. In addition, to evaluate the potential benefits and impediments to implementing PPMOF on their projects, managers considering PPMOF need a systematic and transparent method for analysis and decision making on the applicability of PPMOF.

Objectives and Methodology

The objectives of the research on which this paper is based were: (1) to update those factors influencing PPMOF decisions and develop a decision framework to assist project teams in considering possible use of PPMOF on industrial projects; (2) to identify the current industry practices for evaluating the applicability of prework on a specific industrial project; and (3) to develop a tool to facilitate the decision-making process for evaluating the use of PPMOF on particular projects, based on factors identified.

To achieve the above objectives, the methodology illustrated in Fig. 1 was followed. Industry members represented in the project team ranged from owners to constructors to design firms, each experienced in the use of PPMOF, typically on industrial

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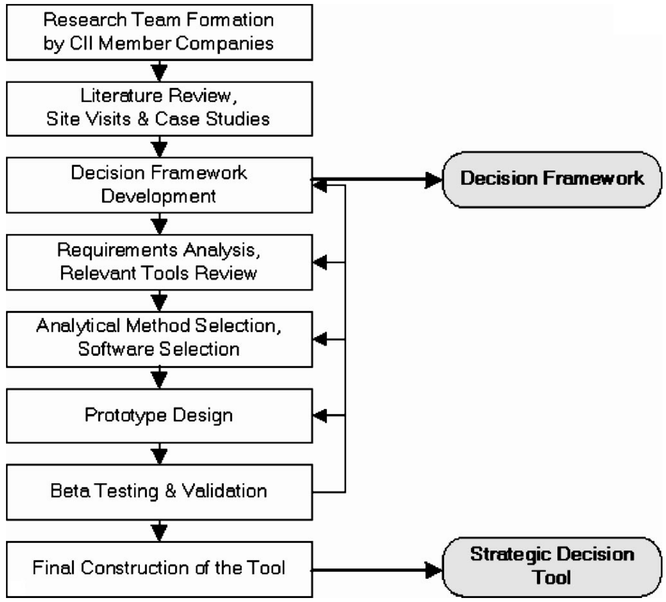

Fig. 1. Research methodology

projects. Leading companies in the area were identified, and a questionnaire was developed to guide collection of information. Results from nine site visits were synthesized into structured reports (Fagerlund 2001). The team reviewed the information and began to structure guidelines and a framework for prework decisions.

Once the research team developed the preliminary decision framework, the development process for the tool began with requirements analysis. The team reviewed the relevant tools described in the "Background Regarding Use of Prefabrication, Preassembly, Modularization, and Off-Site Fabrication" and tried to define specifically what the industry users want or need from such a tool. With the user needs and requirements defined, the team selected an analytical method suitable for evaluating the applicability of PPMOF on a particular project, and a compatible software for embodying the analytical method and user interface. Then a prototype was designed in an iterative manner with the team. The developed prototype tool was subsequently beta tested by potential users in the industry and eventually evolved into the final tool as validators' suggestions for improvements were incorporated into the decision framework as well as the prototype tool.

Background Regarding Use of Prefabrication, Preassembly, Modularization, and Off-Site Fabrication

Past research studies have determined that the appropriate use of PPMOF has the potential to positively impact project performance (Tatum et al. 1987). While these studies investigated the practices of PPMOF and delineated factors to consider when evaluating the use of PPMOF, other research efforts were concerned primarily with the development of the decision support system or framework to aid in evaluating the applicability of PPMOF on a particular project (Fisher and Skibniewski 1992; Murtaza et al. 1993; Murtaza and Fisher 1994; Cigolini and Casteliano 2002).

An early study identified and analyzed practices at the time in the use of PPMOF in both industrial and building construction projects (Tatum et al. 1987). The research then identified the forces prompting their use and implications for a project. Although the applications of PPMOF studied included a wide range of both industrial and building projects, many similar forces were found to drive the use of PPMOF, including: adverse site and local area conditions; demanding schedule; owner or regulatory demands; potential cost savings; and advantages of factory or shop manufacturing conditions. This early study also described general processes for evaluating the use of PPMOF, which were highly project specific, ranging from very systematic studies of feasibility, cost, and schedule for several alternatives, to quick decisions based on intuition and judgment.

A followup research project developed MODEX, a DOS-based expert system, to aid in determining the feasibility of using modular construction technology for a particular process or power plant project. The system performed feasibility analyses based on various factors divided into five influencing factor categories: plant location; labor related; environmental and organizational; plant characteristics; and project risks (Fisher and Skibniewski 1992). This system also performed an economic analysis to determine the impact of modularization on total project cost and schedule, and provided the approximate cost saving or increase that modularization is expected to produce in the project under consideration. Later study validated this system by means of a statistical analysis that concluded with 91% confidence that the results obtained from professionals in the construction industry and MODEX were not significantly different (Murtaza et al. 1993).

A more advanced software tool, named Neuromodex, was also developed based on neural network (NN) architecture to handle inexact and incomplete inputs. The NN-based system uses as inputs the same decision factors as MODEX and provides the final conclusion for a modularization decision. The results obtained from the system were compared with the recommendations provided by human experts. The statistical tests performed to validate the system showed, though limited to ten cases, that neural network results were accurate (Murtaza and Fisher 1994).

A study of prefabrication and preassembly was conducted to estimate recent changes in the use of these methods. Based on a survey of 29 construction professionals with a combined experience of over 700 years, this research found that the average use of these two methods in terms of percent of overall project work had nearly doubled, increasing from 14 to 27%, over the preceding 15 years (Haas et al. 2000). Significant increased use occurred in the areas of equipment, instrumentation, ironwork, mechanical, piping, and structural assembly. According to this study, the three main drivers reported for the use of prefabrication and preassembly are cost, schedule, and workforce issues. This study found that prefabrication and preassembly may also increase craft productivity, improve quality, and reduce labor rates. On the other hand, impediments to prefabrication and preassembly were additional preproject planning and project coordination; increased transportation difficulties; greater inflexibility; and more advanced procurement requirements.

Most recently, a quantitative model was proposed to determine cost variance between "stick-built" and modular construction and aimed at filling the gap between the economic analysis of MODEX and the actual estimation process (Cigolini and Casteliano 2002). First, the model identified the "construction-related" cost items that can be influenced by modularization, including transportation cost, facilities cost, and cost of consumable resources (i.e., water and electric power). The identified cost items, split according to project location perspective (i.e., final site or mod yards), are then quantified using the basic module

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data (module weight, size, and surfaces, pipe materials, equipment, and man hours needed to complete each module). Finally, the model determined the cost variance under the modular and traditional approaches by comparing the cost items by areas where costs originated. However, the model has not considered engineering and procurement-related costs, such as design man hours increased by modularization.

Through the above studies, the drivers, benefits, impediments, and their effects on decision making for PPMOF have been well documented. Nonetheless, the impact on these factors of recent advances in design and information technologies, including three dimensional computer aided design (3D CAD), tracking, and automated positioning/locating has yet to be examined. This research attempted to incorporate the recent technological impacts as well as growing industry challenges such as the skilled labor shortage, and to update factors influencing PPMOF decisions.

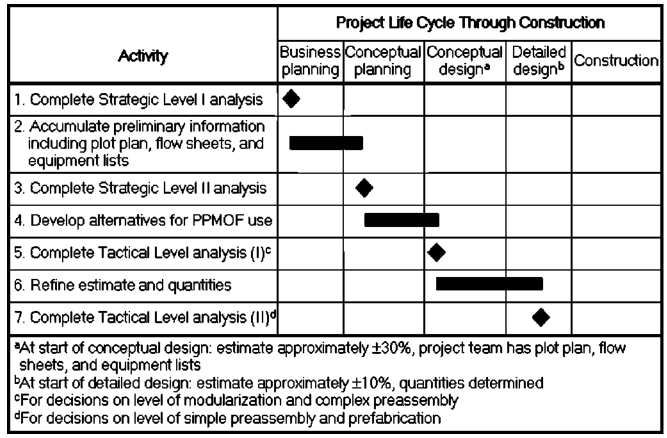

Fig. 2. Decision timing map for prefabrication, preassembly, modularization, and off-site fabrication

Current Industry Practices in Evaluating Use of Prefabrication, Preassembly, Modularization, and Off-Site Fabrication

The data collected as part of this research effort from nine industrial site visits identified several key characteristics common to the current prework practices. First, careful selection of PPMOF may result in a spectrum of decisions rather than all modularization or all stick build. Regarding use of PPMOF, companies have emphasized the question "How much should be used to maximize benefits?" rather than "To use or not to use." Prework should be deliberately applied to areas of a project, not "across the board" as a percentage of work.

Second, prework complexity determines decision timing. Companies involved in full modularization stressed the necessity of early decisions during preproject planning, while in the case of less complex prework such as prefabrication, they could delay decisions until the detailed design phase. However, regardless of the type of prework, every company emphasized the importance of coordination of all project parties. One company took advantage of regular meetings between various design disciplines to coordinate interfaces and routing of various preworked components.

Third, in determining the feasibility of prework, careful analysis of labor differentials from moving work off site was a common factor. Companies carefully evaluated the differences in wage rates, productivity, overall risks, equipment, and overhead costs associated with labor. Companies also used prework to address the skilled labor shortage on site by taking advantage of shop based labor.

Fourth, since shipping options and routes often dictate size and extent of prework, extensive transportation planning, and expediting was required for adequate use of prework. One company extensively planned transportation routes, including options for expanding or improving existing infrastructure to meet the optimum prework size requirements. Another company maintained a specific department to solely handle this transportation requirement. Before shipping prework components, companies also stressed thorough shop testing and verification. One company minimized shutdown to the existing operations by testing equipment prior to installation. Finally, companies viewed prework as a form of outsourcing that allows the work to be done where it is done best and cheapest, with the advantage of economies of scale.

In addition to these key characteristics of current prework practices, the collected data also revealed key enabling technologies that support the use of PPMOF, including computer design and visualization, information technologies, automated fabrication, and tracking technologies. A more detailed description and exploration of current PPMOF practices can be found in Fagerlund (2001).

Levels of Decision Framework Developed in This Research

An appropriate decision-making process for PPMOF should allow for variable timing, since PPMOF provides a spectrum of potential implementation choices rather than imposing an "all or nothing" decision. Decision timing considerations often depend on the level or type of PPMOF, though earlier decisions are generally best for maximizing benefits of PPMOF. In principle, modularization and complex preassembly require earlier decisions than do simple preassembly and prefabrication. The use of modularization is often decided early during preproject planning (i.e., conceptual planning), since modularization shipping envelopes and interfaces typically dictate many constraints of detailed design. Modularization decisions made at the start of detailed design result in large cost premiums for additional engineering. In contrast, many decisions to preassemble or prefabricate components can be made during or after the detailed design phase. In these cases, efficient use of PPMOF is limited by the level of design already complete.

To help industry practitioners effectively deal with this nature of PPMOF decisions, the researchers developed a decision framework to facilitate a systematic thought process, and a decision timing map (Fig. 2) to identify recommended points in the project life cycle to help determine the level and scope of PPMOF. The decision framework is divided into three levels, allowing for variable timing of decision making. The first and second levels are designed to provide insight into the applicability of PPMOF based on primary drivers and impediments. They are strategic in nature and directed at global project goals and objectives. Strategic Level I is intended to serve as a business planning screening tool to identify major drivers and impediments to PPMOF. Using the form presented in Fig. 3 that contains a concise list of questions concerning these major drivers and impediments, this level of analysis can be conducted to initially evaluate the feasibility of using PPMOF.

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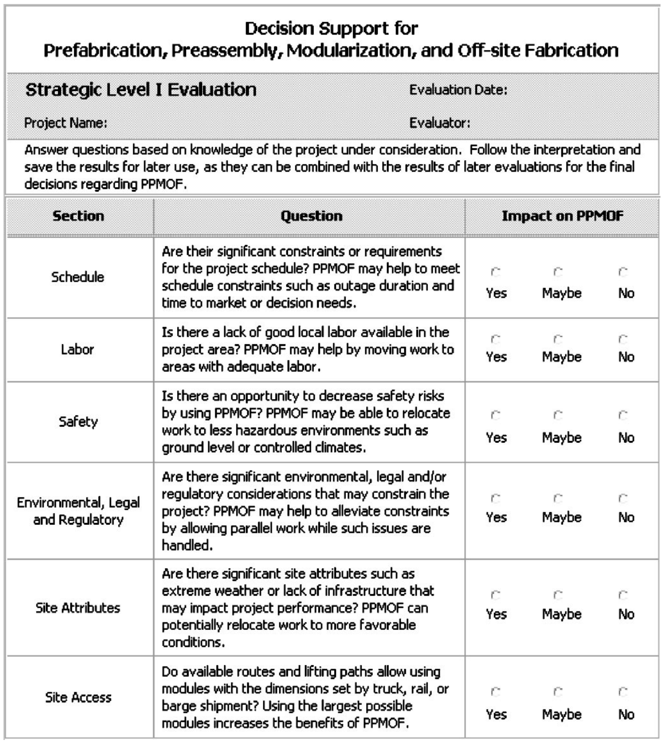

Decision Support for
Prefabrication, Preassembly, Modularization, and Off-site Fabrication

Strategic Level I Evaluation Evaluation Date:

Project Name: Evaluator:

Answer questions based on knowledge of the project under consideration. Follow the interpretation and save the results for later use, as they can be combined with the results of later evaluations for the final decisions regarding PPMOF.

Section	Question	Impact on PPMOF
Schedule	Are their significant constraints or requirements for the project schedule? PPMOF may help to meet schedule constraints such as outage duration and time to market or decision needs.	Yes Maybe No
Labor	Is there a lack of good local labor available in the project area? PPMOF may help by moving work to areas with adequate labor.	Yes Maybe No
Safety	Is there an opportunity to decrease safety risks by using PPMOF? PPMOF may be able to relocate work to less hazardous environments such as ground level or controlled climates.	Yes Maybe No
Environmental, Legal and Regulatory	Are there significant environmental, legal and/or regulatory considerations that may constrain the project? PPMOF may help to alleviate constraints by allowing parallel work while such issues are handled.	Yes Maybe No
Site Attributes	Are there significant site attributes such as extreme weather or lack of infrastructure that may impact project performance? PPMOF can potentially relocate work to more favorable conditions.	Yes Maybe No
Site Access	Do available routes and lifting paths allow using modules with the dimensions set by truck, rail, or barge shipment? Using the largest possible modules increases the benefits of PPMOF.	Yes Maybe No

Fig. 3. Strategic level I analysis

Strategic Level II analysis is designed for use during pre-project planning to delve into the areas highlighted in Level I analysis to further determine PPMOF feasibility as project definition increases. This level of analysis requires slightly more knowledge about the project that may include site location, plot plan, processes, as well as general characteristics regarding infrastructure, required labor, permitting, and legal issues. Because of this information requirement, Strategic Level II analysis may be performed well in conjunction with evaluation of process technology and site alternatives. The Level II analysis of the framework is separated into ten sections corresponding to ten factor categories. Each category contains detailed questions regarding the decision factors, varying from four to ten. Table 1 lists the categorized decision factors used in this Strategic Level II analysis. Table 2 provides descriptions and examples for a selected subset of decision factors used in the Strategic Level II analysis. Strategic Level II analysis is implemented in the form of a spreadsheet program. The analytical method underlying its development as a computerized tool is presented in the next sections as well as a detailed description of the tool.

The final step of the decision framework, a tactical level analysis is focused on a cost comparison to determine feasibility and scope of PPMOF at the level of quantity based estimating. The suggested timing of the analysis is during the conceptual design phase and in some cases later in the beginning of detailed design. The tactical level analysis would be used for less complex types of PPMOF such as simple preassembly and prefabrication, as this research effort found that many types of simple preassembly and prefabrication decisions were often based on detailed cost, labor, and schedule comparisons with conventional options. Once several cases of varying levels and scopes of PPMOF have been identified, a detailed tactical analysis can be executed to compare costs between the stick built and PPMOF options. The total cost impact is based on the combination of additional costs and cost

Table 1. Categorized Decision Factors Used in Strategic Level II Analysis

Category	Factor
Schedule	Shortened schedules
	Planned shutdowns, outages, or turnarounds
	Late business decisions
	Early startup benefits
	Timing of environmental or other project permitting
	Time limitations related to shipping and transportation
	Equipment or materials with long lead-time
	Risks associated with schedule penalties
	Rewards for early project completion
	Requirements to get product to market rapidly
Cost	Overall project cost control
	Overall project cash flows
	Requirements to meet new regulatory or other imposed requirements
	Future reuse value
	Specific local economic factors
Labor	Labor productivity
	Overall or peak labor density requirements (quantity of workers)
	Local, regional, or national labor availability
	Availability of skilled labor
	Project-specific requirements such as licenses for craft workers
	Labor agreements or jurisdictional issues
	Sufficiency of labor in a multiple project environment
	Stability of labor cost
	Local/Regional political considerations
	Multiple shifts of construction workers
Safety	Unusual site or regional hazards
	Ongoing facility operations
	On-site labor density
	Increased risk from high elevations, confined spaces, known toxic atmospheres
	Contractual monetary incentives for a better project safety record
	Reductions in insurance costs
	Heavy lifts
	Regulatory requirements
Site attributes	Anticipated weather conditions at the site
	Political issues
	Environmental restrictions
	Local infrastructure to support the project
	Rights-of-way and property boundaries
	Laydown and staging space on the site
	Access onto and on site
	Remote locations with minimal infrastructure
Mechanical system	Mechanical system density (amount of installed items in a given space)
	Grouping or arrangement of mechanical systems
	Maintenance requirements for the facility

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Table 1. (*Continued.*)
Analysis

Category	Factor
	Size of equipment of assembly
	Special material assembly methods (alloy welding, etc)
	Special assembly requirements such as “clean room” conditions
	Electrical system density
	Electrical system routing requirements
Project and contract types	Replication on other projects
	Protection of proprietary technology or methods
	Project goals that include financial incentives
	Supplier/Contractor flexibility to provide a facility that meets owner’s performance requirements
Design	Availability of key project team members in early project stages
	Requirement for early “freezing” of design
	Project and/or Owner’s organizational structure
	Availability of 3D CAD or similar design technology
	Infrastructure (hardware & software) for communications
	Software compatibility for design and for communication
	Flexibility accommodating modifications or expansion
Transportation and lifting requirements	Availability of transportation methods
	Local transportation costs
	Transportation infrastructure
	Permitting
	Risks of loss during transportation
	Impacts of weather conditions
	Insurance and warranties during transport
	Availability of lifting and hauling equipment
	Foundations required for prework items
	Heavy lifts and related planning
Supplier capability	Supplier availability
	Availability of qualified suppliers
	Supplier shop capacity
	Level of sophistication of supplier’s information systems
	Supplier’s availability of on-site representation

savings resulting from the use of PPMOF for each case identified. Fig. 4 shows the approach for cost comparisons between alternatives.

Based on previous experience with suppliers and costs, project teams may not have to carry out extensive evaluation of all the three levels in the decision framework. The extent to which each level of analysis is used for a particular type of prework can depend on the degree to which a company requires justification for prework use. For example, one company may be comfortable basing its decision to use offsite preassembly on the results of a relatively subjective analysis of the project drivers and impediments at the strategic level. Another company may feel more comfortable with authorizing certain forms of prework only after thorough and detailed cost analyses.

Background Regarding Prior Decision Making Tools

In an attempt to capture human expertise in the domain of PPMOF, several research efforts were made to develop computerized tools: MODEX and Neuromodex (Fisher and Skibniewski 1992; Murtaza et al. 1993; Murtaza and Fisher 1994). Decision methodologies applied to the tools draw upon technologies related to artificial intelligence that aspires to emulate human thought. Table 3 shows how MODEX and Neuromodex structured the decision-making process for the use of modularization in particular and what computer technologies they involved.

For the detailed feasibility analysis, comparable to the Strategic Level II analysis in this research, MODEX calculates the total weighted score using predetermined relative weights on factors and categories and makes a recommendation, conventional or modular construction, with the level of confidence of the advice, based on its knowledge base. For the final stage of analysis, economic study, the user gives MODEX the estimated project cost/schedule, and in turn, MODEX gives the user cost savings (or loss) and schedule reduction possible by adopting some degree of modularization, based on its knowledge base combined with a database. The knowledge base contains decision rules on modularization, and the data base stores a cost summary of realized modular construction projects and their relative cost differentials. These databases would likely require updating or indexing for current use, and the software would need to be updated for current computer operating systems, although MODEX has been used in practice in the past by some companies. With these updates it is in principle still a viable approach to decision making regarding modularization.

Neuromodex took the pattern recognition approach of artificial NNs which recognizes that the human decision makers are not aware of what rules motivate their decision (Burke 1991). Neuromodex uses several decision factors related to a particular project as a set of inputs to form a pattern, then associates the input pattern with one of output patterns that represent level of modularization applicable on the project: conventional, low or high partial modularization, or extensive modularization (Murtaza and Fisher 1994). Neuromodex could elicit implicit knowledge, expertise, or rules of human experts from a certain set of training examples with which its neural network is trained. This rationale for Neuromodex is consistent with the view that construction experts do not use explicit rules to arrive at decisions based on limited information and may even fail to rationalize their decisions involving a good number of interrelated factors, as with the PPMOF decision problem (Moselhi et al. 1991). Despite the ability to exploit the strengths of NN, Neuromodex would depend on the availability of a large amount of historical data and assume that the past modularization decisions were correct (Burke 1991). Nonetheless, Neuromodex represents a rational and effective decision tool approach in principle.

Developing New Decision Tool

The companies investigated as part of this research effort agreed that a decision tool would be useful for determining feasibility of PPMOF both for internal and client justification, although most of

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Table 2. Partial Listing of Descriptions and Examples for Decision Factors Used in Strategic Level II Analysis

Factor	Description	Examples of the impact that specific forms of prefabrication, preassembly, modularization, and off-site fabrication may have on the project
Late business decisions	Prework has the potential to compress the installation schedule by utilizing higher shop productivity and multiple fabrication sites, allowing postponement of final business decisions related to bringing a product to market.	Pharmaceutical company manufactured the production facility while awaiting government approval of a product; product producer planning for market conditions/prices; wet acid plant built modular while permits were pending.
Overall project cash flows	Prework has the potential to provide more options for cash flow since work can be completed sooner or delayed without affecting targets.	Bulk chemical facility was estimated for both stick and modular construction. Since the modular schedule was a year shorter (2 years vs. 3 years stick), the owner opted to build modular but postpone construction one year. The postponement freed money for other projects for the year and allowed better design information to be obtained.
Availability of skilled labor	Prework can move critical work to locations where adequate skilled labor is available.	Having a "centralized" location for prework may provide for training and repeatability of systems (specialized people are not necessarily sent to different locations, and this expertise can be used to train new people for those times when someone needs stationing).
Ongoing facility operations	Reducing in the number of workers and types of crafts may reduce impacts on any ongoing operations.	Equipment in a steel mill was preassembled to reduce construction impact on existing operations; chemical plant expansion built modular to reduce impact on existing operations.
Local infrastructure to support the project	Prework can relocate activities to locations where there is adequate infrastructure such as supplies, vendors, housing or hotels, and power supply.	Existing pipe racks, road limitations, overhead clearance, culverts, bridges, utilities, and other site obstacles may require removal and/or replacement.
Mechanical system density (amount of installed items in a given space)	Efficiencies in layout and quality control may be realized through prework of piping intense projects.	Process areas in chemical plants; in some cases, density may be defined as less than 75–100 ft^2 per worker.
Protection of proprietary technology or methods	Prework can be conducted at secure locations where proprietary items can be assembled and protected.	Process technology developer protects proprietary components with prework.
Availability of 3D CAD or similar design technology	Some complex designs for prework benefit from the ability to design with 3D CAD.	3D CAD allows walkthroughs, improved visualization, and interference checking; communication of ideas and layout are also quicker through 3D images.
Transportation infrastructure	Transportation routes must be evaluated to handle the proposed shipments (road and bridge height and weight restrictions).	Bridge load restrictions, turning curve radii, road width, and overpass clearance may restrict size and weight of prework components; other restrictions may include overhead power lines, grade limitations, seasonal road load limits, and rail restrictions for size and weight.
Availability of qualified suppliers	Prework suppliers requirements may include certain certifications or levels of quality.	A supplier requirement for structural steel preassemblies for a chemical plant included tons per month of prefabricated elements; suppliers may be required to handle a certain amount of testing capacity, such as hydrotesting or x-ray testing.

them were using in-house expertise and relied on the judgment of experienced project managers, rather than utilizing tools already on the market. To be useful and effective in evaluating the applicability of PPMOF, such a tool should: (1) serve as a means to facilitate a decision process dialogue, rather than calculating an answer, even if correct; (2) provide transparency in invoking decision makers' judgment on relative importance of decision factors; (3) be easy to maintain and modify; and (4) help them sort out what factors drive or impede the use of PPMOF on the project under consideration.

In view of these requirements and needs, a computerized tool was developed, based on the preliminary decision framework, to aid project teams in evaluating the applicability of PPMOF on particular projects. The development efforts were focused on the Strategic Level II analysis because the earlier decisions at the strategic level have more influence on the overall project performance. Also, later decisions at the tactical level are more likely governed by the organization's standard operating procedures, as they are essentially based on a cost comparison between the conventional method and a particular application of PPMOF.

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To evaluate the feasibility of PPMOF at the strategic level, the weighted factor method was considered the most suitable. This method embraces the concept of relative-importance weights which is central to the current decision-making paradigm that the feasibility of PPMOF at the strategic level is often based on relative weighting by experienced personnel of decision factors. Specifically, this evaluation method provides a convenient means for the user to: (1) weigh decision factor categories separately, (2) combine scores on the categories according to his or her relative importance weights, and (3) obtain information on what factors could drive or impede the use of PPMOF on the project under consideration.

In fact, this decision methodology is one that has been applied to MODEX's feasibility analyses, yet with predetermined relative weights on factor categories and without transparency in the process. Arguably, the weighted factor method has the score of qualitative questions depend on the person answering (Cigolini and Casteliano 2002), and it might be difficult for the users to come up with their own relative importance weights as they go through its subjective process in evaluating the applicability of PPMOF (Adelman 1992). However, the relative importance weights represent personal judgments that should be made by the decision makers, and unlike the tactical level decisions involving cost comparison, this subjective assessment cannot be replaced with any mechanical procedures. Since the timing and nature of the earlier decision on applicability of PPMOF prescribes subjective judgments, the weighted factor method for the developed tool should be effective for subjective evaluation at the strategic level.

To develop a tool that embodies the selected evaluation method and user interface into the preliminary decision framework, a spreadsheet program sufficed. As the evaluation method selected is not computationally complex and does not require a data base for operation, it can be implemented most efficiently in a spreadsheet format. The choice of the research team was Microsoft® *Excel* which provides capabilities to develop a customized application by virtue of the relatively easy to learn programming language, Visual Basic for Applications (VBA). The VBA enabled the project team to make the user interface flexible, simple, easy to use, responsive, and self-explanatory by allowing for direct use of a variety of hierarchical *Excel* objects (Albright 2001).

As the research team communicated their views regarding the prototyped tool and defined the user needs more precisely, potential users' views were integrated into the tool throughout the development process that iteratively involved test, evaluation, and subsequent refinement of the user interface, the scoring system of the analytical method, and even the decision framework.

Strategic Decision Tool Developed in This Research

The strategic decision tool developed is intended to help its users recognize the factors to consider in making early decisions on the use of PPMOF for an industrial project. It can also help identify the drivers and impediments to PPMOF that managers need to address in a project execution plan. Analyzing the drivers and impediments for the project considering the additional information obtained over the preproject planning phase will allow project teams to develop several cases of varying levels of PPMOF.

In the evaluation process, the tool guides users through several steps as shown in Fig. 5. Users are first asked to assign weight factor values to each of ten factor categories comprising the Strategic Level II of the decision framework. Each weight factor value represents the users' judgment of the relative importance of its corresponding category. The weight factor values can be any number between 0 and 5. As users proceed to assign weight factor values to each category, weight factor percents are updated and quantify the users' relative assessment of the importance of categories. Fig. 6 illustrates example weight factor values in the "Summary" sheet. Although users can modify or assign weight factors after completing the detailed questions, the researchers recommend completing this before proceeding with the detailed questions. When users have assigned weight factor values, they click on the button captioned "Detailed Questions" and are guided to the next step to answer ten categories of detailed questions, starting with the "Schedule" category. As the user completes the detailed questions in each of the ten categories, "Weighted Scores" and the "Final Score" in the last column of the "Summary" sheet are continuously recalculated.

Fig. 7 illustrates the layout of a detailed questions section. Each section of the analysis focuses on a category of factors identified at the top of the table for that section. Column 1 assigns a unique number to each question and gives a brief title. Column 2 describes the impact that specific forms of PPMOF may have on the project. Examples of the impact can be viewed by moving the cursor over the triangle at the upper right corner in the "Description" cell. The next group of six columns allows the user to assess the impact of PPMOF more specifically, using a scale ranging from −5 to +5. A positive score indicates that project conditions favor PPMOF regarding the specific factor; a negative score indicates that project conditions favor field work regarding the specific factor. If the user considers any factor to be not applicable to a specific project under evaluation and does not wish to include the factor in the immediate evaluation, he or she will assign "N/A" to the corresponding question.

If users do not provide any response, either a score or N/A, for a detailed question, then the question is considered unanswered. Only when all the detailed questions in a category are answered are the raw scores for each factor averaged across the category to provide a category raw score. Otherwise, the "Average Raw Score" for a category remains "Incomplete" as shown in Fig. 7. The average category raw score is obtained by dividing the sum of factor scores by the number of factors given in the category and then transferred to Column 2 "Average Raw Score" of the "Summary" sheet. The difference between N/A and a zero score is important. While a factor given N/A will never be considered to be a driver or impediment to PPMOF for the "Reports of Extremes," one given a zero score may be shown in the reports, described later. The detailed questions in each of the ten categories can be found in Song (2002).

Once users complete answering the last category of detailed questions, they are guided back to the "Summary" sheet (Fig. 6). Here users can assess the final score based on their average category raw scores and assigned weight factor values. They are also given the opportunity to modify or refine the assigned weight factor values. Column 3 of the "Summary" sheet is the relative weight that users have assigned to each category. Column 5 is the weighted score of each category, calculated by multiplying the average category raw score by the weight factor value the users select. Summing the weighted scores across categories gives the final score of the users' evaluation which is intended to indicate the desirability of PPMOF strategy on the project under consideration. Any final decisions on scope of PPMOF implementation may need to be supported by the tactical level analysis.

Completing all of the detailed questions as well as their rela-

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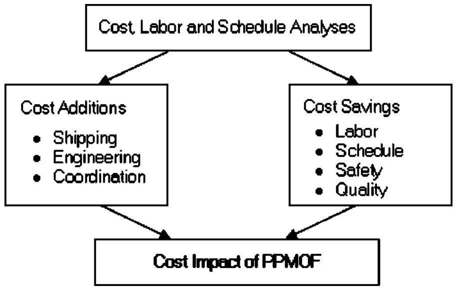

Fig. 4. Structure for cost comparisons among prefabrication, preassembly, modularization, and off-site fabrication alternatives

tive weights, specific drivers and barriers to PPMOF for the project under consideration results in the "Reports of Extremes" (Fig. 8). The reports give two top ten lists of the factors most strongly supporting PPMOF (drivers) and of the factors most strongly against PPMOF (impediments) for the project under consideration. The most important criterion in ranking the extremes factors is the weighted score in Column 3 of the "Reports of Extremes." Weighted scores for each extreme factor are calculated by multiplying the factor raw score in Column 2 by its category weight factor percent. For instance, if a user has assigned weight factor values in the "Summary" sheet so that "Schedule" category accounts for 20% of all weight factor values (i.e., its weight factor percent is 20%) and assigns +5 (Pro PPMOF) to a factor in the Schedule category, the factor's weighted score is 5*20% or 1.00. As stated earlier, any factor given N/A cannot be a candidate for a driver or impediment to PPMOF for the project under users' consideration. These reports can be viewed by clicking on the "Reports of Extremes" button at the bottom of the "Summary" sheet (Fig. 6). Uncompleted detailed questions or weight factor values will however restrict access to the reports.

Validation of Decision Tool

Before the final construction of the tool described, the prototype of the tool was beta tested to determine: (1) whether the prospective users generally like the tool; (2) what they consider to be its strengths and weaknesses; and (3) what changes they would suggest for improving it. The beta testing represents a validation method, assessing in the judgment of the testers whether the tool actually improves their performance as decision makers for PPMOF. Thus, of primary concern was the usefulness and effectiveness of the tool to the decision-making process for PPMOF.

The validation of the prototype tool was performed by industry experts. The beta test package included a cover letter explaining the intent of beta testing, a draft research summary providing

Table 3. Decision-making Process and Technologies of MODEX and Neuromodex

	Underlying computer technology	
Level of analysis	MODEX	Neuromodex
Initial feasibility analysis	Expert system	—
Detailed feasibility analysis	Expert system	Neural network
Economic analysis	Decision support and expert systems	—

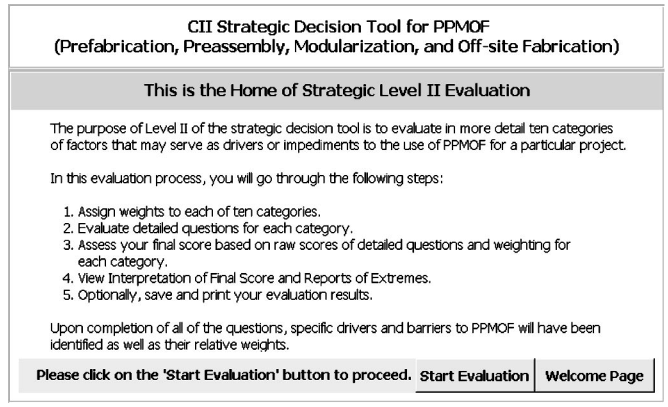

Fig. 5. Evaluation process of strategic decision tool

some background on preliminary results of this research, draft guidelines explaining how to use the tool, and a survey questionnaire with a copy of the spreadsheet prototype tool. The projects evaluated with the tool were in stages varying from preproject planning to construction to completion. They all were industrial facilities, with estimated project costs ranging from US$20 to $350 million, and approximate total schedule duration from 15 to 32 months. Eight sets of a survey questionnaire were completed by project managers, construction managers, and an owner's process designer. They were completed either individually or as a team, and the contributors came from owner, construction management, project management companies, general contractor, and subcontractor/supplier.

The beta testing of the prototype tool validated its effectiveness in the decision-making process for PPMOF, as conveyed by the survey responses. Specific short-answer questions about the prototype tool covered its usefulness, ease of use, and helpfulness in the decision-making process, and team alignment. In general, the respondents considered the tool to be effective, with its usefulness favored in most cases, the ease of use in fewer cases. The survey questionnaire also had an open-ended question that gave the participants an opportunity to recommend improvements to the prototype. They also took this opportunity to indicate what they perceived to be strengths of the prototyped tool. Specific comments included:

1. "Flexible in letting the user weigh the factor weights;"
2. "Brings all of the factors associated with the decision on PPMOF into the evaluation; the series of questions raised some additional issues that had not been considered when first evaluating the applicability of PPMOF;"
3. "Helps to highlight areas of concern for extra and early planning; it would give a team the items to emphasize in early planning for the modular project if the decision to modularize have already been made;"
4. "Provided a tool for the project team to use to evaluate the execution strategy;"
5. "When completed as a team, input from all contributors would be solicited and considered;" and
6. "Examples added to the description of factors were very helpful to narrow the team's focus as a team can have a different interpretation or reaction to each decision factor."

Specific suggestions for improvement to the prototype tool were related to ease of use, the scoring system, semantics, etc. The researchers incorporated the feedback from beta testing into the final construction of the tool. Since its release by the Construction Industry Institute, the tool has been requested and used by several

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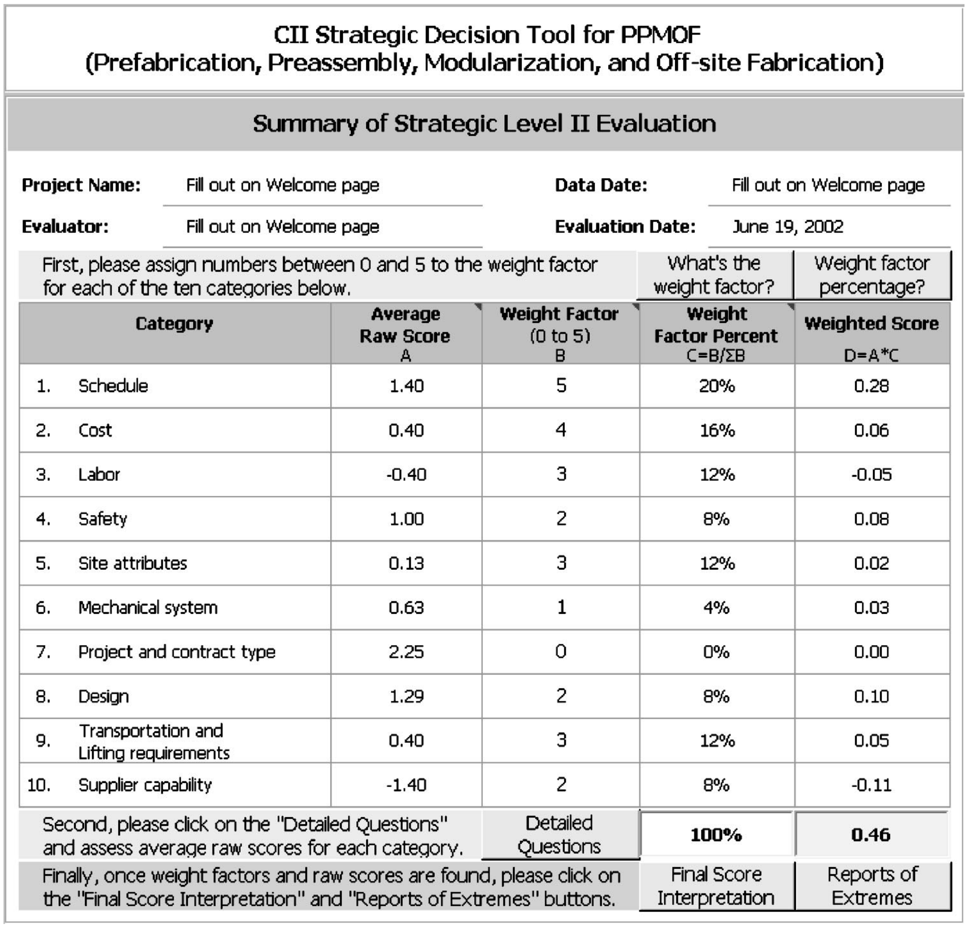


CII Strategic Decision Tool for PPMOF
(Prefabrication, Preassembly, Modularization, and Off-site Fabrication)

Summary of Strategic Level II Evaluation

Project Name:	Fill out on Welcome page	Data Date:	Fill out on Welcome page
Evaluator:	Fill out on Welcome page	Evaluation Date:	June 19, 2002

First, please assign numbers between 0 and 5 to the weight factor for each of the ten categories below. | What's the weight factor? | Weight factor percentage?

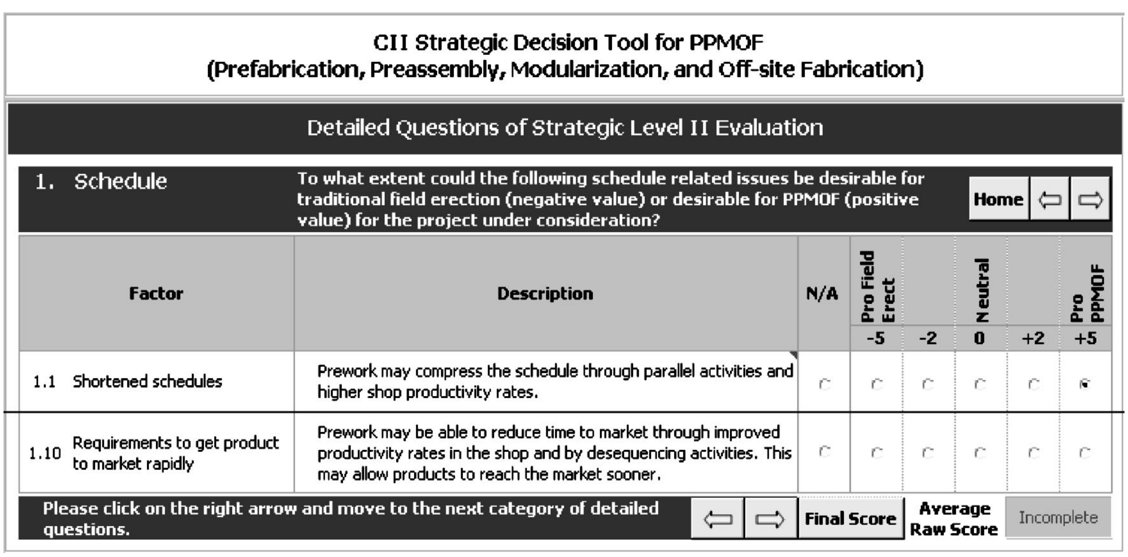
Category	Average Raw Score A	Weight Factor (0 to 5) B	Weight Factor Percent C=B/ΣB	Weighted Score D=A*C
1. Schedule	1.40	5	20%	0.28
2. Cost	0.40	4	16%	0.06
3. Labor	-0.40	3	12%	-0.05
4. Safety	1.00	2	8%	0.08
5. Site attributes	0.13	3	12%	0.02
6. Mechanical system	0.63	1	4%	0.03
7. Project and contract type	2.25	0	0%	0.00
8. Design	1.29	2	8%	0.10
9. Transportation and Lifting requirements	0.40	3	12%	0.05
10. Supplier capability	-1.40	2	8%	-0.11
Second, please click on the "Detailed Questions" and assess average raw scores for each category.		Detailed Questions	**100%**	**0.46**
Finally, once weight factors and raw scores are found, please click on the "Final Score Interpretation" and "Reports of Extremes" buttons.			Final Score Interpretation	Reports of Extremes

Fig. 6. Example summary sheet of strategic decision tool

companies, and early feedback is positive but unquantified.

Conclusions and Recommendations

Successful implementation of prefabrication, preassembly, modularization, and off-site fabrication, collectively termed PPMOF or prework for the purpose of this research, requires systematic analysis and early decision-making based on project factors. Prework can offer a substantial opportunity to improve project performance and has become more viable with recent advances in design and information technologies. The PPMOF decision framework and tool described here: (1) serves as a means to fa-



CII Strategic Decision Tool for PPMOF
(Prefabrication, Preassembly, Modularization, and Off-site Fabrication)

Detailed Questions of Strategic Level II Evaluation

1. Schedule — To what extent could the following schedule related issues be desirable for traditional field erection (negative value) or desirable for PPMOF (positive value) for the project under consideration? — Home

Factor	Description	N/A	Pro Field Erect -5	-2	Neutral 0	+2	Pro PPMOF +5
1.1 Shortened schedules	Prework may compress the schedule through parallel activities and higher shop productivity rates.						
1.10 Requirements to get product to market rapidly	Prework may be able to reduce time to market through improved productivity rates in the shop and by desequencing activities. This may allow products to reach the market sooner.						

Please click on the right arrow and move to the next category of detailed questions. | Final Score | Average Raw Score | Incomplete

Fig. 7. Example category of detailed questions for strategic decision tool

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CII Strategic Decision Tool for PPMOF
(Prefabrication, Preassembly, Modularization, and Off-site Fabrication)

Reports of Extremes for Strategic Level II Evaluation

Project Name: Fill out on Welcome page **Data Date:** Fill out on Welcome page
Evaluator: Fill out on Welcome page **Evaluation Date:** June 19, 2002

Factors Most Strongly Supporting PPMOF

Rank	Raw Score	Weighted Score	Factor	Category	Question No.
1	5	1.00	Shortened schedules	Schedule	1
1	5	1.00	Timing of environmental or other project permitting	Schedule	5
2	5	0.60	Local, regional, or national labor availability	Labor	3
3	5	0.40	Reductions in insurance costs	Safety	6
3	5	0.40	Requirement for early "freezing" of design	Design	2
3	2	0.40	Late business decisions	Schedule	3
3	2	0.40	Early startup benefits	Schedule	4
3	2	0.40	Rewards for early project completion	Schedule	9
4	2	0.32	Requirements to meet new regulatory or other imposed requirements	Cost	3
4	2	0.32	Future reuse value	Cost	4

To save and print your evaluation results, please go to the Final Score (Summary) sheet and press the "Save" and "Print" buttons. **Final Score** **Final Score Interpretation**

Fig. 8. Example reports of extremes: Factors most strongly supporting prefabrication, preassembly, modularization, and off-site fabrication

cilitate a decision process dialogue; (2) provides transparency in invoking decision-makers' judgment on relative importance of decision factors; and (3) helps users sort out what factors drive or impede the use of PPMOF on the project under consideration.

The beta testing of the prototype tool and its subsequent adoption by industry practitioners validates usefulness. The tool has been found to help ensure a thorough assessment of the factors associated with PPMOF decisions. It also helps to highlight the items to emphasize in the execution strategy, and it helps to align a project team. The tool may also be used to train personnel less experienced in the application of PPMOF. Clearly, the ability of users to assign category weights is both a strength and a weakness. Regression and factor analyses to assign weights based on project outcomes would be ideal. However, it is unlikely that a large enough database would ever be available to provide statistically valid results.

Industry practitioners have expressed strong interest in the development of Tactical level analysis procedures. Such procedures are worth developing and then implementing into software to help: (1) develop specific options applicable to implementing PPMOF decisions; (2) determine cost, schedule and labor impact; and (3) assess risk associated with each option. However, analysis at this level tends to become excessively dependent on project type and company procedures, so general approaches and databases have been difficult to develop. Finally, the decision framework and the tool presented in this research should be adapted to other areas of the construction industry, such as building construction, that can benefit from the use of PPMOF.

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