Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization

James T. O'Connor, M.ASCE[1]; William J. O'Brien, M.ASCE[2]; and Jin Ouk Choi, S.M.ASCE[3]

Abstract: Modularization is a well-established technique that can improve the construction industry by exporting a portion of site-based work to fabrication shops. However, its application in the industry is limited. The Engineering, Procurement and Construction (EPC) industry needs new approaches to reach higher levels of modularization. The purpose of this study is to determine what changes in current EPC processes are needed to create an optimal environment for a broader and more effective use of modularization. In creating such an nvironment, it is necessary to know the factors that lead to success. The most influential critical success factors (CSFs; 21 total) have been determined by the expertise of a research team who compiled a detailed list by adding CSF *enablers*. CSF enablers are additional steps that can facilitate accomplishment of the associated CSF. A closer look at the top five CSFs indicates that project teams should pay particular attention to module envelope limitations, team agreement on project drivers, adequate owner-planning resources and processes, timely freeze of scoping and design, and due recognition of possible early completion from modularization. This CSFs analysis and addition of *enablers* provide guidelines and ways to implement strategies for successful modularization in a project and leverages modularization to benefit capital projects. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000842.

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Introduction

Researchers have shown renewed interest in the potential benefits of modularization and related prefabrication and preassembly techniques. The re-emergence of such interest was pointed out by McGraw-Hill (2011) in their Smart Market Report. Modularization technology has evolved such that more sophisticated and complex facilities are subject to its implementation (MBI 2010). Furthermore, as productivity growth in off-site sectors is increasing faster than that seen in on-site sectors (Eastman and Sacks 2008), value gain ought to increase through exporting a portion of site-based work to fabrication shops. Over the next 20 years, its growing prevalence could significantly advance the productivity and competitiveness of the capital facilities sector of the US construction industry (NRC 2009). The extent of modularization is expected to rise with the emergence of building information modeling (BIM), advanced information technology (IT), and automation technology.

However, Lu (2009) identified just how scarcely such techniques are used in America. Also, McGraw-Hill (2011) identified through a survey that only a little over one-third (37%) of building industry players used modularization at high or very high levels (McGraw-Hill 2011). A previous study estimated that the use of prefabrication and preassembly in the industrial sector had, from 1981 to 1999, nearly doubled. The extent of modularization in industrial construction, however, had not changed significantly over decades (Haas et al. 2000). Construction Industry Institute (CII) Research Team (RT) 171 noted that, while some companies had successfully employed prefabrication, preassembly, modularization, and off-site fabrication (PPMOF), the industry in general had yet to fully capitalize on PPMOF's potential to improve projects (CII 2002).

Definition of Terms

Modularization is by no means a new concept and as such has been utilized many times in the past, has been discussed extensively, and has been defined in many ways. The literature has substantial variation in definitions and terminology. For consistency, this paper has adopted the following:

Modularization: "the preconstruction of a complete system away from the job site that is then transported to the site. The modules are large in size and possibly may need to be broken down in to several smaller pieces for transport" (Haas et al. 2000).

Module: "a major section of a plant resulting from a series of remote assembly operations and may include portions of many systems; usually the largest transportable unit or component of a facility" (Tatum et al. 1987).

Prefabrication: "a manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of a final installation" (Tatum et al. 1987).

Preassembly: "a process by which various material, prefabricated components and/or equipment are joined together at a remote location for subsequent installation as a unit. It is generally focused on a system" (Tatum et al. 1987).

Off-site fabrication: "the practice of preassembly or fabrication of components both off the site and onsite at a location other than at the final installation location" (CII 2002).

[1]C. T. Wells Professor of Project Management, Dept. of Civil, Architectural and Environmental Engineering, Univ. of Texas at Austin, 1 Univ. Station C1752, Austin, TX 78712. E-mail: jtoconnor@mail.utexas.edu

[2]Associate Professor, Dept. of Civil, Architectural and Environmental Engineering, Univ. of Texas at Austin, 1 Univ. Station C1752, Austin, TX 78712. E-mail: wjob@mail.utexas.edu

[3]Ph.D. Candidate, Dept. of Civil, Architectural and Environmental Engineering, Univ. of Texas at Austin, 1 Univ. Station C1752, Austin, TX 78712 (corresponding author). E-mail: jinouk.choi@utexas.edu

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PPMOF (prefabrication, preassembly, modularization, and off-site fabrication): several manufacturing and installation techniques, which move many fabrication and installation activities from the plant site into a safer and more efficient environment (CII 2004).

PPMOF is sometimes collectively termed as *prework* in the industry (Haas et al. 2000; Song et al. 2005). The authors found that the building sectors vary in how they define the above terms, even disagreeing (since the building and industrial sectors are different) on adopting *module*, which was defined by Tatum et al. (1987), CII (2002), and Gibb (1999). The term off-site production (OSP) has often been identified in the modular building industry (Blismas et al. 2006). Readers may understand well how these sectors differ and adopt the definition appropriate to their industry.

Research Trend

Since its introduction, modularization's process has been well established, its values and benefits widely recognized. Many previous studies have examined or identified the benefits of using modularization and determined that, when properly used, the technique offers a great opportunity to improve project performance in industrial projects (Song et al. 2005; Tatum et al. 1987). A full discussion of the historical development is outside the scope of this paper, but the authors have summarized the research trends on the topic according to the industrial and building sectors, advanced technologies in the modular building industry, and CII studies.

An early study conducted by Tatum et al. (1987) documented applications of PPMOF in both industrial and building construction projects. The research identified the driving factors of PPMOF, including adverse site and local area conditions, contractor or supplier capabilities, advantages of manufacturing conditions, demanding schedule, owner or regulatory demands, potential cost savings, specialized design requirements, and standardization.

Haas et al. (2000), seeking to determine trends and effects on the construction workforce, conducted a study of prefabrication and preassembly but excluded modularization. The study determined the relative weight of the drivers, advantages, impediments, as well as the impact of technology on prefabrication and preassembly. The three drivers of the use of prefabrication and preassembly were schedule, workforce issues, and economic factors. The study also identified that in prefabrication and preassembly, productivity and safety levels were higher, skill levels the same, and wage levels lower. Haas et al. (2000) argued that these techniques had the potential to reduce project duration, improve productivity, reduce labor costs, and shorten the supply chain.

Song et al. (2005) identified factors that influence decisions on using PPMOF. The authors developed a strategic decision tool for evaluating the applicability of PPMOF in industrial projects. They concluded that what was required for successful implementation of PPMOF was systematic analysis and early decision making. Furthermore, they contended that PPMOF had become more viable with recent advances in design and IT.

Over the past few decades, the house-building industry has been rigorous in adopting and utilizing off-site techniques (Pan et al. 2012). Many researchers have conducted studies on off-site techniques in the building industry. The history of the technique's development is well documented in Gibb's (1999) publication. There, Gibb formally addressed off-site fabrication regarding its context, principles, applications, and implications in the building sector. Thus far, studies have identified and examined the benefits, drivers, barriers, and success factors in preassembly building industry from owner's perspective (Gibb and Isack 2003); the benefits and disadvantages of offsite technologies in the UK building industry (Blismas et al. 2006; Goodier and Gibb 2007); and the benefits, barriers, and applications of standardization and preassembly in construction industry (Pasquire and Gibb 2002). Yet, even in the building modular industry, researchers have found there to be deficient holistic studies on the critical success factors (CSFs) of building modularization and what enables such CSFs.

The key technologies to promote the use of PPMOF are automation, visualization (BIM), and simulation. Thus, various studies have been conducted in these areas (Alwisy and Al-Hussein 2010; Han et al. 2012; Mohamed et al. 2007; Mohsen et al. 2008; Olearczyk et al. 2009). Neelamkavil (2008) presented an overview of the types of automation techniques prevalent in the modular and prefabrication areas. These included the following: robotic automation, crane and movement automation, virtual reality and simulation, schedule automation, sensor-base control, and order processing automation.

CII has conducted several studies in PPMOF, funding studies (summarized in the preceeding) conducted by Tatum et al. (1987) and Song et al. (2005). RT 171, led by the CII (2002), identified the benefits and limitations in the use of PPMOF in the industrial sector and provided a knowledge-based guide and tool to improve upfront decisions.

Many past studies have explored the benefits of industrial modularization as well as some of the barriers to its application. Also, many studies on off-site techniques in the building industry have been found. What they have so far failed to do, however, is raise modularization to an optimum level within the construction industry. Moreover, few studies have sought to identify, from expert practitioners' practices, either its CSFs or its enablers holistically.

Literature of Success Factors for Higher Levels of Modularization

Many factors go into implementing industrial modularization successfully. Tatum et al. (1987) determined that the use of PPMOF can bring about many changes in projects and add new demands on or complexity to project organization, engineering, procurement, planning, monitoring, coordination, communication, and transportation. Also, design change flexibility decreases. In the building modular sector, Gibb and Isack (2003) identified several success factors, from the owner's viewpoint, for preassembly implementation. Those success factors are early design freeze, reasonable lead times, sufficient time for presite prototyping, early vendor involvement, and owner's understanding of its benefits and limitations.

For higher levels of modularization in the industrial sector, however, there is no holistic research on critical success factors. Thus, before identifying such critical success factors (CSFs), the authors, drawing on the literature, have tried to come up with potential success factors. The result of this effort is a foundation for CSFs analysis. Documented success factors include early consideration, alignment on drivers, new technology, design freeze, standardization, fabrication infrastructure, and improvement in logistics. It is important to note that comparison of success factors in the industrial industry versus the building industry is beyond the scope of this paper. This research may need to be followed up with a study that characterizes industrial modularization.

Early Consideration

A modularization strategy should ideally be incorporated at project inception (Burke and Miller 1998; Post 2010). Song et al. (2005) insisted that successful implementation of PPMOF requires systematic analysis and early decision making based on specific factors of the project. Given the issues involved in early decision making, they presented a tool developed by CII (2002) that assists in modularization decision making. The tool, called MODEX, helps experts determine the feasibility of modularizing a project.

Alignment
Greater use of modularization could be facilitated by unrestrained involvement of construction, during all phases of work, with design (Akagi et al. 2002; Tam et al. 2007). If all parties were aligned, they would all be informed of the various benefits, thus increasing the likelihood of successful implementation.

New Technology
Technology can also help modularization gain wider use. Advances in design and information technologies, CII points out, go a long way towards allowing modularization to become more viable (CII 2002). One such example is the increasing use of and advances in 3D technology and building information modeling (BIM).

Automation is expected to help the prefab and modular construction industry (Neelamkavil 2009). According to Neelamkavil (2009), automation technologies include automated design, automated supply network and materials management, robotics automation in prefab factories, automated construction site, virtual reality and simulation, and scheduling automation and sensor-based control.

Design
Modularization could be more feasible if design followed the best modular design principles. To do this, one of the most basic changes would be in the sequence of design (Akagi et al. 2002). Furthermore, to make designs more applicable to modularization, the literature suggests controlling design variants. For example, Ericsson and Erixon (1999) urge designers to reduce interdependency between elements. As a controlling design variant, Milberg et al. (2002) presented the potential for tolerance allocation techniques by using 3D modeling in generating, evaluating, and selecting more robust designs.

Standardization
The shipbuilding and automotive industries have recommended the use of standard/subsequent design. The automotive industry to a great extent applies the idea of design for manufacturing (Ulrich et al. 1993; Venkatachalam et al. 1993). In their modern shipbuilding analysis, CII recommends the use of block design and thus standard design (CII 2007). By standardizing modules, cost benefits can be obtained through resulting economies of scale (CII 2011). In the building industry, Gibb and Isack (2001) presented briefly on standardization and its implications from the client's perspective.

Fabrication Infrastructure
Purpose-built module fabrication facilities can make module construction more feasible. Akagi et al. (2002) assert that building a factory designed specifically to build modules for nuclear power plants onsite allowed for a greater number of modules to be built. An initial investment in fabrication facilities is necessary (CII 2011) and such facilities would need to have a large output to successfully amortize its expenses (Lapp and Golay 1997).

Improvements in Logistics
Lastly, inexperienced contractors and owners can meet their cost and schedule goals by working with integrated service companies. Such companies provide integrated planning, logistics, heavy lifting, and transport (Youdale 2009). Modular construction could gain wider acceptance with greater availability of larger cranes.

Summary of Literature Review

Much of the literature recognizes the value, benefits, and uses associated with industrial modularization. These may pertain to increased productivity, lower capital costs, greater quality, safer working environments, reduced site safety exposures, as well as causing less impact on the environment. However, the benefits of modularization do not come free. The impediment to higher levels of modularization may include the barriers of cost, engineering design, procurement, logistics, and expertise and culture. These studies put forward many ideas on how to overcome impediments. Documented success factors in this literature review are early consideration, alignment on drivers, new technology, design freeze, standardization, fabrication infrastructure, and improvement in logistics. Nonetheless, further research is needed on how to optimize in a systematic way modular approaches.

Objectives

Research Team (RT) 283 (O'Connor et al. 2013) was established to address, through collaborative research, this situation. In framing their purpose, RT 283 posed this question: What changes or adaptations in traditional project work processes are required to create an optimum environment for broader and more effective use of modularization? More specifically:

- What CSFs drive modularization's success?
- Who is responsible for these?
- When are they most critical?
- How frequently is each achieved, and what special efforts are needed?

The scope of the research concerns primarily the industrial subsector, including process and manufacturing facilities such as offshore facilities, petro-chemical plants, power plants, and pharmaceutical plants, among others.

Organization of Paper

This paper presents the following CSF analyses: an overview of high-impact CSFs, CSFs' implementation timing and lead responsible party, CSF frequency level, and enablers for each CSF. Finally, the paper summarizes findings from three case studies.

Research Methodology

Critical Success Factors Methodology

Brainstorm Value Drivers and Impediments
The researchers compiled a list of impediments to the wider use of modularization. This was done through an open discussion of the status of the modularization strategy, a discussion based first on the existing literature and the research team's collective expertise contributions and then a brainstorming effort. This list enabled the qualifying and quantifying of all the success factors affecting modularization. Identifying value drivers enhanced the influence of the success factor list. In this list, 72 potential success factors were documented. The full list of 72 potential success factors can be found in CII Research Report 283 (O'Connor et al. 2013).

Rank CSFs on Impact
With a list of 72 potential success factors, the researchers came up with a survey quantifying the impact of each factor on modularization efforts and the extent of their use. Thus, the research surveyed the team members using a structured instrument to facilitate consistent and comparable collection of team member knowledge. Responders were asked to rank the impact of each potential success factor from zero (0) to four (4); zero being not applicable or no impact and four being the highest impact. The researchers analyzed the results and were able to identify which success factors are most

important and selected 21 CSFs, which ranked the impact score above three (3).

Assess CSFs for Current Frequency of Occurrence

The researchers also created a second survey that quantified today's frequency of each CSF's occurrence after identifying 21 CSFs. Both the impact survey and the frequency survey were conducted with the same sample–19 research team members (response rate 100%). This survey helped identify which CSFs were essential for attaining higher levels of modularization use. Combining this information with the impact data helped us create a focus for organizations.

Identify Enablers to Facilitate CSF Accomplishment

For the 21 CSFs, the following supporting items were added:

- Enablers: The research team deems these necessary for an organization seeking to enable higher use of modularization within their projects.
- Lead organization: The organization must be identified that is most likely to lead the effort to reach higher levels of modularization with respect to each CSF. The lead organization is typically the organization in which the cause of the CSF originates.
- Timing: To address each CSF and maximize its impact, it is necessary to deploy at the optimal time organizational resources.

These findings were also developed by the RT and reviewed by the external validation committee.

Validation by External Experts

Based on the research team members' recommendations, more than 15 external experts from various companies were invited to review the findings, with most of them accepting. The validation committee had about a month to review the draft of research findings and return their individual feedback. The researchers and the research team members went through every comment received item by item from the validation committee and reacted to them according to three response types: (1) responded, (2) disagreed with or neglected, or (3) already in place/no change needed. Detail of responses to the comments can be found in O'Connor et al. (2013).

Research Team Background

The CSFs are part of the research results produced by CII RT 283. The 21-member team was made up of experts from the construction industry and academic institutions. Over two years, they worked at developing the tool and documenting the research findings.

Surveying these members' backgrounds was necessary to determine the level of experience available, to organize efforts according to strengths, and to help locate potential sources for case studies. RT 283 has a total of 450+ years of experience and has been involved in 170+ modular projects constructed in the last 5 years in 13 countries. The RT had two members from academia; industry representatives ranged from five owners, eight contractors and design firms, and six fabricators. Each member had experience and was familiar with industrial projects that used modular construction from various sectors like power, oil, gas, LNG, petroleum, and so forth.

External Validation Committee Background

The external validation committee, consisting of 14 volunteers from the construction industry, validated the research product drafts on CSFs. A survey found that the committee has 458+ years of experience and, in the last 5 years, had undertaken work on 123+ modular projects.

Results and Analysis

Overview of High-Impact Critical Success Factors

The *Critical Success Factors Methodology* section explained how the CSFs were identified; the potential success factors (total 72) were analyzed for impact by 19 modularization experts in the research team (on a 4.0 scale). There were 21 potential success factors that received a score of 3.0 or more. These were determined to be CSFs and are presented as follows:

- CSF#1 Module Envelope Limitations (impact score 3.83): Preliminary transportation evaluation should result in understanding module envelope limitations.
- CSF#2 Alignment on Drivers (3.79): Owner, consultants, and critical stakeholders should be aligned on important project drivers as early as possible in order to establish the foundation for a modular approach.
- CSF#3 Owner's Planning Resources & Processes (3.58): As a potentially viable option to conventional stick building, early modular feasibility analysis is supported by owner's front-end planning and decision support systems, work processes, and team resources support. Owner *comfort zones* are not limited to the stick-built approach.
- CSF#4 Timely Design Freeze (3.58): Owner and contractor are disciplined enough to effectively implement timely staged design freezes so that modularization can proceed as planned.
- CSF#5 Early Completion Recognition (3.42): Modularization business cases should recognize and incorporate the economic benefits from early project completion that result from modularization and those resulting from minimal site presence and reduction of risk of schedule overrun.
- CSF#6 Preliminary Module Definition (3.42): Front-end planners and designers need to know how to effectively define scope of modules in a timely fashion.
- CSF#7 Owner- Furnished/Long Lead Equipment Specification (3.42): Owner-furnished and long-lead equipment (OFE) specification and delivery lead time should support a modular approach.
- CSF#8 Cost Savings Recognition (3.42): Modularization business case should incorporate all cost savings that can accrue from the modular approach. Project teams should avoid the knee-jerk misperception that modularization always has a net cost increase.
- CSF#9 Contractor Leadership (3.39): Front-end contractor(s) should be proactive—supporting the modular approach on a timely basis and prompting owner support, when owner has yet to initiate.
- CSF#10 Contractor Experience (3.37): Contractors (supporting all phases) have sufficient previous project experience with the modular approach.
- CSF#11 Module Fabricator Capability (3.37): Available, well-equipped module-fabricators have adequate craft, skilled in high-quality/tight-tolerance modular fabrication.
- CSF#12 Investment in Studies (3.32): In order to capture the full benefit, owner should be willing to invest in early studies into modularization opportunities.
- CSF#13 Heavy Lift/Site Transport Capabilities (3.32): Necessary heavy lift/site transport equipment and associated planning/execution skills are available and cost competitive.

- CSF#14 Vendor Involvement (3.28): Original Equipment Manufacturer (OEMs) and technology partners need to be integrated into the modularized solution process in order to maximize related beneficial opportunities.
- CSF#15 Operations and Maintenance (O&M) Provisions (3.26): Module detailed designs should incorporate and maintain established O&M space/access needs.
- CSF#16 Transport Infrastructure (3.22): Needed local transport infrastructure is available or can be upgraded/modified in a timely fashion while remaining cost competitive.
- CSF#17 Owner Delay Avoidance (3.16): Owner has sufficient resources and discipline to be able to avoid delays in commitments on commercial contracts, technical scope, and finance matters.
- CSF#18 Data for Optimization (3.05): Owner and Pre-FEED/FEED contractor(s) need to have management tools/data to determine the optimal extent of modularization, i.e., maximum net present value (NPV) (that considers early revenue streams) versus % modularization.
- CSF#19 Continuity through Project Phases (3.00): Disconnects should be avoided in any contractual transition between Assessment, Selection, Basic Design, or Detailed Design phases; their impacts can be amplified with modularization.
- CSF#20 Management of Execution Risks (3.00): Project risk managers need to be prepared to deal with any risks shifted from the field to engineering/procurement functions.
- CSF#21 Transport Delay Avoidance (3.00): Environmental factors such as hurricanes, frozen seas, or lack of permafrost, in conjunction with fabrication shop schedules, do not result in any significant project delay.

A closer look at the top five CSFs reveals that project teams should pay particular attention to module envelope limitations, team agreement on project drivers, adequate owner-planning resources and processes, timely freeze of scoping and design, and due recognition of possible early completion from modularization.

CSFs by Project Phase & Responsible/Lead Party

The CSFs were analyzed for the best timing of deployment by project phase and to identify the best responsible or lead party. Figs. 1 and 2 illustrate the findings from these analyses. Who is responsible for seeing that CSFs are fully addressed? The project owner primarily, with the contractors being secondary. As for timing, ensuring the success of modularization is most critical during the Assessment and Selection phases. Interestingly, only 15% of CSFs are related to the Execution and Startup phases. To facilitate successful modularization, significant owner involvement is clearly needed early on.

CSFs Frequency Analysis

CSFs were also evaluated for how frequently they were accomplished. It became clear that more industry initiative is needed to raise the frequency of those poorly performing CSFs. Fig. 3 illustrates the results of the frequency analysis when combined with the impact analysis.

The frequency survey result of CSFs is represented visually in Fig. 4 where it is mapped into a stairway graphic. The purpose is to show that increased efforts are needed to accomplish the Occasional, Rare, and Very Rare CSFs, especially for those with high impact rankings (as indicated in the CSF numbering). To increase modularization, for example, what appear to be challenging but valuable opportunities are owner's planning resources and processes (Rare & #3), and contractor leadership (Rare & #9) (Fig. 4).

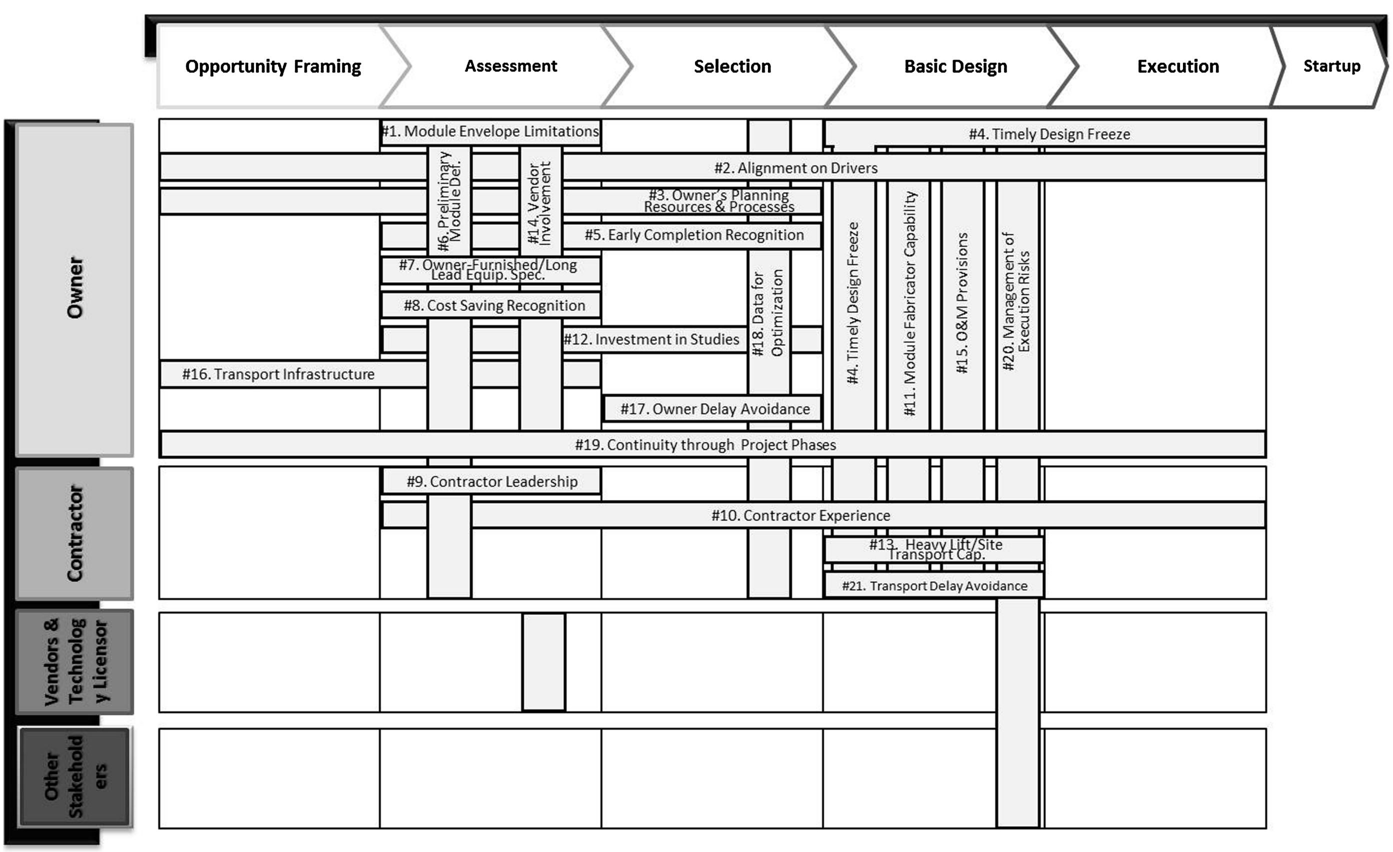

Fig. 1. CSFs fabric: timing versus responsible/lead party

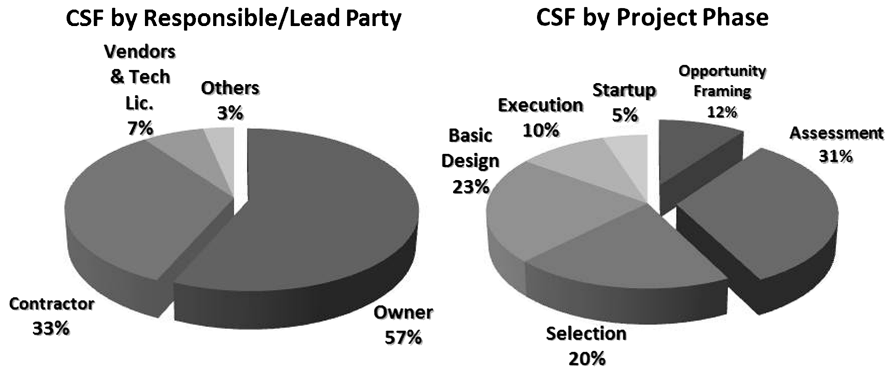

Fig. 2. CSF distribution by responsible/lead party and timing of implementation

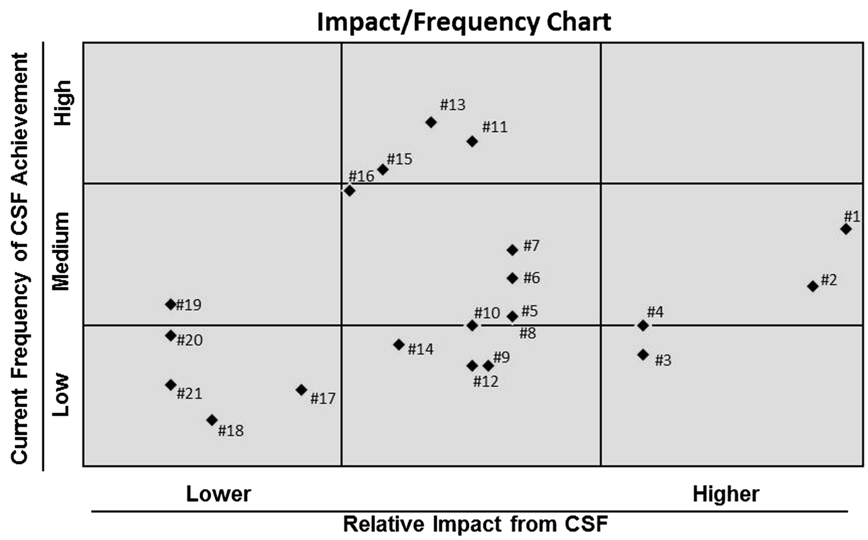

Fig. 3. CSF frequency and impact

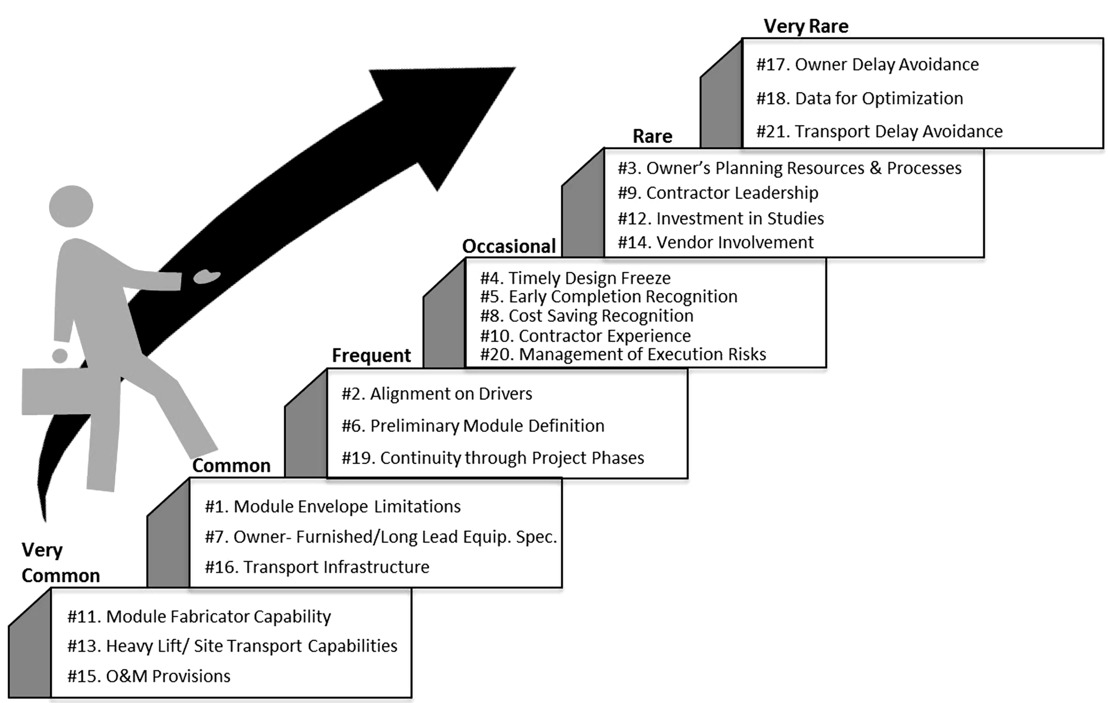

Fig. 4. CSF frequency stairway

While the research did not formally examine any justifications or causal factors related to CSF frequency of accomplishment, possible explanations for the Rare/Very Rare CSF accomplishments may involve the following: (1) less attention focused on risk contingency (particularly as it pertains to delay avoidance); (2) disinterest in facilitating modularization optimization (by failing to capture key data); (3) supply chain complexity and uncertainty (particularly in early project phases); (4) vendor reluctance to support early owner planning; and (5) contractor tendency to follow the owner's lead, rather than lead itself.

CSF Enablers

CSF *enablers* are additional steps that can facilitate accomplishment of the associated CSF. The enablers address resources, tools, and actions. Some enablers are labeled *stretch enablers*, which denote approaches that offer greater, potentially step-wise advancement. The enablers are listed below.

Enablers for CSF#1 Module Envelope Limitations
1. Early logistics and transportation evaluation should identify costs, critical constraints, and risks, from proposed fab yard locations to the workforce.
2. Owner and pre-FEED contractor should be familiar with existing plans to upgrade regional transportation infrastructure.

Enablers for CSF#2 Alignment on Drivers
1. Owner should get module and construction experts involved (including cost estimating) to help define drivers and ensure alignment.
2. CII alignment process and tools should be modified to better address critical alignment issues pertaining to modularization

Enablers for CSF#3 Owner's Planning
1. Need a business case process and decision support system incorporating all modular variables, including major equipment.
2. Need work processes that incorporate all modular considerations; could modify CII project definition rating index (PDRI), a tool that offers a method to measure project scope definition for completeness (CII 2009) and front-end loading (FEL) business feasibility processes and tools to better support owner concept studies, keying all activities to FEL milestones.
3. Owner resources for this can be outsourced.
4. Need to have the right owner culture. Owners would benefit from a tool to assess their culture's adaptability to modularization.
5. Owner needs to be able to support the modularization philosophy in several ways: managerially, technically, and commercially.
6. Teams would benefit from ready access to historical performance data on modular benefits: quality, safety, productivity, labor camp, scaffolding, smaller field management staffs, wage and fringe benefits deltas, etc.

Enablers for CSF#4 Timely Design Freeze
1. Managed and timely staged freezes of process flow diagrams (PFDs), equipment, plot plans, and piping and instrumentation diagram (P&ID) information to allow for reliable planning and estimate of module costs and savings.
2. Effective alignment with all key stakeholders and timely sign-offs on scoping documents.
3. Owners conduct uncertainty tracking of scope drivers and timely validation of scope-related assumptions.
4. Modular-friendly plot plans and P&IDs that show module boundaries.
5. STRETCH: Expand, at every opportunity, application of design one-build many, and at all possible scales (from components to whole units).

Enablers for CSF#5 Early Completion Recognition
1. Owners need to recognize the economic benefits from early completion: early product sales, lower contractor site-overhead costs, lower owner site-supervision costs, fewer site-safety and site-productivity risks (downtime and costs), among others. These are too often ignored or their impact underestimated.
2. Owners need to be more aware of how much time (i.e., overall project duration) can be saved from the modular approach. Analysts familiar with such impacts and benefits should be involved in early analyses of concepts.
3. Owners and contractors need to acquire duration performance benchmarking data from past modular and stick-built projects and information on associated schedule risks.

Enablers for CSF#6 Preliminary Module Definition
1. Given as a premise for this item: Understand stick-built scope versus modular scope and understand parametric on work–hours/cuft for different types of facilities. Opportunity Framing phase produces a module philosophy, while Assessment phase produces module strategy and module definition.
2. Avoid merely drawing lines on conventional stick built designs. Early on, employ experienced personnel with knowledge of manufacturing processes and optimal layout of equipment.
3. Use PFDs, plot plans, and preliminary P&IDs to *cube* the modules, considering optimal transport weight and size, operating systems/subsystems, O&M accessibility, optimal density, vertical versus horizontal benefits, available real estate, operating energy losses, site accessibility, system/component testing isolation, optimal valve and junction box locations, optimal/balance structural steel, site construction accessibility, minimization of piping field welds, timing of system/subsystem startup, complete instrument loops, needs for utility lines (water, air, electric, steam lines, etc.), among others.
4. Refine plot plan and general arrangement drawing with input from the heavy lift/transport and construction team, as well as the fabricator. Seek to optimize the modules based on these discussions.
5. Optimize work-hour density of modules without impacting operability/maintainability; conduct a MH/cuft density check.
6. Avoid modules too small with too many interfaces.

Enablers for CSF#7 Owner-Furnished Long Lead Equipment Specification
1. Need early information on reliable equipment lead times for OFE procurement.
2. Need to avoid situations where OFE size is wrong or nonoptimal for the modular approach (e.g., aspect ratio); this could limit transport options.
3. Need timely availability of certified (or reliable) equipment drawings for OFE.
4. Owner should consider all opportunities for equipment preassembly, including insulation, cladding, dress-out, etc.
5. Need accelerated owner procurement process to get equipment interface information in time to support module engineering.
6. Need accelerated owner procurement process to ensure equipment is delivered for timely inclusion in module.
7. Need owner ability to fund OFE procurement in a timely way, often prefinancial investment decision.

8. Owner may need specialist assistance for ensuring that equipment specifications are supportive of the modularization approach, including schedule/sequence aspects.
9. Need additional early design effort to develop vendor instructions on freeze-critical variables. Need vendor ability to fix or freeze critical variables, such as envelope, weight, and location of tie-in points (e.g., nozzles) for reliable interface management and to allow subsequent engineering to proceed.

Enablers for CSF#8 Cost Savings

1. Types of construction cost savings may need to include the following: site labor camp cost, including camp O&M, food stocks, energy costs, etc.; weather impacts on labor productivity; labor wage rate differentials, including fringe benefits; eliminated or reduced scaffolding cost: material and labor, supervision; avoidance of hot work permits; productivity gains from much less elevated work; less labor per diem paid; improved total project safety from moving work-hours to a controlled shop environment; materials much closer to fab shop, fewer delays; easier second shifts (given lighting, wind containment, etc.); shop productivity improvements over those on job site; and less labor turnover for nontravelers; among others.
2. Cost increase items may include the following: additional structural steel, shipping costs, engineering costs, larger cranes at the site, and dual-contractor organizations, among others.
3. Owners and contractors need to acquire cost-saving benchmarking data for these items from past modular projects.

Enablers for CSF#9 Contractor Leadership

1. Owner and contractor processes and tools should incorporate timely modular considerations as a part of standard operating procedure.
2. When owner initiative is lacking, assessment, selection, and basic design contractor(s) should display courage on the modular subject in conversations with owner.
3. Contractors can use experienced-based presentations to illustrate compelling reasons to support timely modularization assessments.

Enablers for CSF#10 Contractor Experience

1. Owners should add modular experience to the criteria for selection of any analysts/contractors from pre-FEED through detailed design and give it significant weight in the selection decisions.
2. Contractors should acquire experience with the method, working with experienced partners as needed.

Enablers for CSF#11 Module Fabricator Capability

1. Starting in the Selection phase, owners/contractors should conduct timely screening studies and prequalifications of candidate fabrication shops to ensure that project needs are matched with capable fabricator(s).
2. The detailed survey of fabricators should address the following: proximity/transportation to site; available capacity; capabilities and training of personnel on typical engineering versus custom/specialized engineering packages; ability to grow with new additional projects (land, facility expansion, financial backing, additional support in personnel/administrative/scheduling/supervision/etc.); yard throughput; quality and safety performance metrics; financial stability; previous experience all activity highlighting relevant projects; among others.
3. Ensure that fabrication facilities and adjacent transport infrastructure are adequate or can be upgraded in a timely fashion while remaining cost competitive.

Enablers for CSF#12 Investment in Studies

1. Owner financing and cash-flow plans should support early studies as needed.
2. Projects with current marginal business case for modularization may benefit from more in-depth early studies.
3. Even projects with a strong business case for modularization will benefit from early studies on the modular work scope, cubing, technology and equipment selection, interface management, and constructability. These studies have the potential of revealing additional benefits from modularization.
4. Early site investigations will also enhance modularization planning.
5. STRETCH: As a business development strategy, specialists may benefit from research and development efforts focused on modular technologies and processes that could accelerate project schedules and/or reduce costs.

Enablers for CSF#13 Heavy Lift and Site

1. Get a heavy lift team involved as early on as possible. Heavy lift studies should be conducted to determine construction constraints and risks.
2. Conduct a constructability review early. Perform enough design work to develop preliminary layouts and options that will provide estimates of module sizes and weights.
3. See previous Module Preliminary definition for insights into load sizes, dimensions, etc.
4. Cost implications can be estimated with early discussions on module size, lift equipment size, and lift/site transport spatial constraints.

Enablers for CSF#14 Vendor Involvement

1. Gain a better understanding of how different manufacturing technologies and equipment can better support the modular approach. Issues for consideration include process/equipment scalability, preferred size restrictions for OEM equipment, alternative geometries and orientations, and concurrent fabrication techniques to shorten the critical path, among others.
2. Invite OEMs and technology partners to participate in discussions on how they could have their equipment modularized. Help them understand what the objectives are and how the modular approach can facilitate their products/services.
3. Request appropriate equipment data early on from OEMs and technology partners, and make sure they remain involved in discussions regarding modularization of their equipment.
4. STRETCH: Broaden the vendor's involvement with the industry to produce industry-level solutions that are better integrated with modular solutions.

Enablers for CSF#15 O&M Provisions

1. Confront the misperception that modularization adversely impacts O&M access.
2. Ensure that credible, qualified owner O&M representatives are brought in early to participate in initial studies and discussions, and to define O&M space/access requirements.
3. Follow up with 3D model reviews with O&M personnel frequently during the design process.
4. Ensure understanding among designers that the modular approach is not to compromise O&M space/access needs.

Enablers for CSF#16 Transport Infrastructure

1. Work with regional infrastructure authorities to ensure the adequacy of local transport infrastructure and associated usage policies.

2. Work with regional infrastructure authorities and local manufacturing owners to set up funding mechanisms to support and maintain adequate transport infrastructure.
3. Owner and contractor collaborate on planning of future upgrades to transport infrastructure, involving outside parties with similar interests. These could include bathometric survey, upgrades of offloading facilities, collaboration with regional authority on usage fee/tax base for funding, etc.
4. STRETCH: Establish a regional transportation infrastructure authority to master plan and fund industry infrastructure needs.

Enablers for CSF#17 Owner Delay Avoidance
1. Owners must understand what is required of them to be successful with the modular approach and, on a timely basis, to be able to recognize and solve problems (such as pertain to funding, equipment approvals, design efforts, etc.).
2. If owner staffing is deficient, owner must be willing to hire external assistance on a timely basis.

Enablers for CSF#18 Data for Optimization
1. Owner and module specialist (as required) need to agree on how to run NPV analyses on several different design cases, each with varying levels of modularization, without compromising the owner's proprietary assets or information.
2. Optimum modular solution should not be assumed, but quantitatively analyzed, with consideration of early completion benefits.
3. Schedule and cash-flow effects should be considered in the analyses.

Enablers for CSF#19 Continuity through Project Phases
1. Given any organizational or contractual discontinuities at a transition from one phase to another results in lack of continuity in the areas of strategy and planning, stakeholder engagement, and risk management among other areas. Special efforts are needed to ensure continuity from one phase to the next, particularly with respect to all module (and related) decisions taken.
2. A key owner role is to ensure continuity from one phase to the next and from one contractor to the next. No other entity can play that critical role, and the owner will be effective in this role only if he/she is knowledgeable about all the progress achieved and critical decisions taken to date.
3. Using the same contractor for two or more phases will help eliminate problems associated with discontinuity of team personnel.

Enablers for CSF#20 Management of Execution Risks
1. No change in principle: The party most capable of mitigating a particular risk should be the assigned owner of that risk.
2. On a modular project, risk management and mitigation are, for a variety of reasons, particularly important. For example, with modularization, engineering must start earlier, vendor data exchange needs can be out of sequence, and control of change must be more effective. All of these can increase risk.

Enablers for CSF#21 Transport Delay Avoidance
1. Weather, environmental events, and related risks must be considered in the planning and scheduling of module transport.
2. Risk analysis and contingency planning are needed to help assure expected transport performance.
3. As a part of risk mitigation, all potentials for delay should be addressed with potential work-around solutions.

Case Study Findings

Overview of Case Study

As the principles upon which an increase in the use of modules in projects were better identified and developed, validation through case studies was necessary. This study carried out case studies using a comprehensive interview guide in an effort to relate the information on modularization in key projects. The study provided assessment results of implementing CSFs. This case study includes three project summaries: drivers, barriers, and accomplishments of CSFs.

Case Study Methodology

Create Interview Guide

Through many iterations and reviews, the research team developed an extensive and inclusive interview guide. The objective was to obtain as much valuable information as possible from case studies. The guide emphasizes the importance of putting all the concepts of increased modularization in context by obtaining information about the interviewee, the selected case study project in general, information about the modular facet of the project, and performance information among other items. The interview guide was generated in accordance with social science interview principles for effective research with respect to validity and reliability (Isaac and Michael 1995). Details are available in O'Connor et al. (2013).

Conduct Interviews

After suitable case studies were identified and interviews conducted, three final modularization projects were selected. The managers or experts involved in the projects were interviewed as per the interview guide. Several meetings and discussions clarified the context of the projects and comments from the interviews.

Analysis of Results

An analysis of the results from the interviews was used to reveal all aspects of a project. This analysis was combined with all issues related to impediments to increased modularization or drivers of modularization. Many of the concepts presented in the CSFs correspond to issues observed in the case study analysis and the study therefore pursued the validation of such tools through an extensive case study.

Case Study Results

To better understand the different circumstances and characteristics of each project, the researcher investigated the background of each as well as each one's project information such as the total installation cost (TIC), phase when the interviews were conducted, industrial sector/subsector, original primary project driver, project location, sizes of the modules (largest, smallest, and heaviest), first assessed modularization (phase at time of first assessment of modularization), and percent modularization (sum of modules' work hours exported to fabrication shops versus originally planned stick-built site work hours for total work scope). Table 1 summarizes information about selected case study projects. These three projects were executed by different companies in different locations with a variety of project characteristics, drivers, and constraints.

Project drivers were important factors impacting the owner's decision to go with modularization or to select the level of the modularization. The original primary project driver in choosing modularization, for all three projects, was cost. A specific driver in the three projects was labor benefits (cost, productivity, and supply). Project A accomplished the highest modular extent

Table 1. Three Projects Summary

Feature	Project A	Project B	Project C
Total installation cost (TIC)	$32 billion	$260 million	$1.75 billion
Phase at Jan. 2012	Execution	Execution	In operation
Sector	Oil and gas (downstream)	Power	Oil and gas (downstream)
Original primary project driver	Cost and schedule	Cost	Cost
Site	Australia	Mexico	Canada
Largest module	40.7H 80.9L 40.8W 5,466mt	10H 58L 11W 30 tons	24H 24L 120W 160 tons
Smallest module	22H 36L 31W 1,313mt	6H40L8W 15 tons	N/A
Heaviest module	6,780 mt	350 tons	160 tons
First assessed modularization	Opportunity framing	Opportunity framing	Assessment
Percent modularization (%)	75	40	43
Total number of accomplished CSF	18	14	15
Accomplished CSF #	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19, and 20	1, 2, 5, 6, 8, 9, 11, 13, 14, 15, 16, 19, 20, and 21	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 14, 15, 16, 17, and 18

(75% modularization), which might be due to more project drivers and barriers. The following are project drivers by project:

- Project A–Schedule, labor cost, labor productivity, labor supply, site access, and environmental impact.
- Project B–Schedule, labor cost, labor productivity, and labor supply.
- Project C–Labor cost, labor productivity, and labor supply.

Project A had more project barriers because the site was located in a cyclone belt and Class A nature reserve, thus increasing the number of issues related to weather, the environment, and regulations. Furthermore, Project A was expected to have more difficulties since Australia tends to have a high turnover of personnel and labor issues with union agreements. The following is a summary of project barriers by project:

- Project A–Weather (extreme), logistics challenges, environmental impact, labor issues, regulating impact, and team turnover.
- Project B–Weather (extreme), logistics challenges, and IT infrastructure.
- Project C–Weather (extreme), logistics challenges, environmental impact, and labor issues.

CSF accomplishments were assessed by project and are shown in Table 1. The authors presented for validation the case project information regarding CSFs in this paper; and CSFs are found to correlate highly with high levels of modularization use projects. For those interested in further information on these case projects, the full case study findings can be found in O'Connor et al. (2013).

Conclusions and Contributions

Summary of What Was Learned

This research formally identified 21 modularization CSFs. Furthermore, the study identified CSF enablers to provide project organizations and teams with additional guidance on how the CSFs could be achieved. What follows is a summary of the research findings.

1. The top five CSFs indicate that project teams should pay particular attention to module envelope limitations, team alignment on project drivers, adequate owner planning resources and processes, timely freeze of scoping and design, and due recognition of possible early completion from modularization.
2. More industry effort is needed to accomplish the Occasional, Rare, and Very Rare CSFs, particularly for those with high impact rankings such as owner's planning resources and processes, and contractor leadership.
3. More than half of the factors require leadership and implementation by project owners. For successful modularization to occur, the message is clear: substantial owner involvement must occur early.
4. Assessment and Selection phases are of greatest significance for ensuring modularization success through CSFs with regard to timing.

Research Significance

This research was conducted to create an optimum environment for broader and more effective use of modularization. It is anticipated that various professionals in the industry will, from this research, know the answers to the following questions. What are the CSFs that can drive success with modularization? Who is responsible for these? When are they most critical? What special efforts are needed? Specifically, the research findings emphasize that for successful modularization, substantial owner involvement must occur at an early stage of the project. Identified CSFs and enablers will help industry experts to implement modularization successfully, maximizing its benefits.

Needs for Future Research

Ideas for additional future research into modularization include the following:

1. Are there links between modularization CSFs and modularization extent and performance?
2. What expanded or revised CSFs are needed to better suit the other sectors of the industry, such as commercial building, residential, or infrastructure sectors? Are there different barriers to modularization for different industry sectors? If so, what other special industry efforts are needed in each sector to achieve higher levels of modularization?
3. What is the current state-of-the-art method or process for planning logistics, transportation, and handling?
4. What kind of education program is needed to enhance the industry's modularization implementation?
   a. What kind of education module is needed to change the owner's perceptions of modularization, increase their planning resources, and improve modularization's processes?
   b. What kind of education module is needed to improve the leadership and capabilities of a fabricator and a contractor?

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