Defining and Categorizing Modules in Building Projects: An International Perspective

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Abstract: Modularization involves breaking up a system into discrete chunks, which communicate with each other through standardized interfaces, rules, and specifications. It is a broad concept with various interpretations and meanings across research disciplines. The complex-ity and scope of a module is not captured sufficiently and clearly in the construction management and engineering literature, and the impact of modularization across project phases has not been fully explored and articulated. Therefore, the main question addressed in this paper relates to the inherent meaning of *what is a module* in the context of different phases of a building project. In addressing this question, this paper empirically investigates the use of modularity in 15 construction projects situated in Italy, Germany, Brazil, and the United Kingdom. The findings of this research suggest that a design-based and an operations-based perspective of modularity coexist, and that there is the need for an integrated view of modularity across the project lifecycle phases and for collaborative working between designers and site operators. To this aim, a unifying definition of a module in building projects is proposed along with a practical guide to help managers organize project activities for effective modularization. The actual cost analysis of the various modularization strategies provides an interesting avenue for future research. The template proposed also requires wider testing with a wider range of modules.

Author keywords: Modular; Offsite; Prefabrication; Project planning and design.

Introduction

The idea of using modular proportions to regulate the design of buildings has a long history (Le Corbusier 1954). Modular designs and approaches are a useful means for managing complexity (Ethiraj and Levinthal 2004), and help rapidly respond to changing customer requirements (Galunic and Eisenhardt 2001). According to Baldwin and Clark (2000), modularity involves breaking up a system into discrete chunks, which communicate with each other through standardized interfaces, rules, and specifications. Modularization is a broad concept, though, with various interpretations and meanings across research disciplines and market sectors (Cigolini and Castellano 2002). Schaefer (1999) argues that key challenges for a modular system are finding the appropriate number and types of modules as well as defining their interactions and interfaces. This paper addresses the problem of identifying and categorizing modules in building projects.

Numerous sources have bemoaned the lack of progress in adopting new ways of working and modern methods of construction in the industry (O'Brian et al. 2009; Pan et al. 2007). Typical problems that appear to have persisted include incorrect specification, coordinating deliveries and trades on-site, and information flow issues (Gosling et al. 2015), as well as fragmentation and lack of integration across project parties (Briscoe and Dainty 2005). Volatility of workflow, timeliness, and late changes to specification also remain key project risks to be managed (Gosling et al. 2013a). Modular and off-site approaches may help in addressing such persistent problems, but attitudinal issues and the lack of practical guidance are barriers to adopting new methods (Pan et al. 2007; Schoenwitz et al. 2012). Early studies of modularization in the construction sector sought to demonstrate that the savings outweigh any extra design and engineering costs (Glaser et al. 1979; Murtaza et al. 1993), whereas later studies have taken a more reflective evaluation of strengths and weaknesses (Blismas et al. 2006).

Arriving at a precise definition of a module is a challenging task, though, because there has been a proliferation of terms associated with modularity in the literature. These include, among others, off-site, prefabrication, preassembly, modern methods of construction, and industrialized buildings. The collective acronym PPMOF—which stands for prefabrication, preassembly, modularization, and off-site fabrication (Khalili and Chua 2013; O'Connor et al. 2014; Pan et al. 2012)—serves as a reminder of the blurring of boundaries between different concepts. Modular buildings have also been linked with lean construction initiatives (Ikuma et al. 2010) and with the growing off-site movement (Pan et al. 2012) as well as the move toward industrial standardization (O'Connor et al. 2015). However, as noted by Doran and Giannakis (2011), there is little consensus or guidelines as to the precise understanding of a module.

Bodies, institutes, and governments are interested in encouraging faster, more cost-effective methods of construction, often

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encouraging off-site and prefabrication approaches to contribute to this agenda (Bradbury 2012; Institute of Mechanical Engineers 2015; Modular Building Institute 2015). A number of concerns motivate the current study. Firstly, the construction management and engineering literature does not capture sufficiently and clearly the complexity and scope of a *module*. Secondly, the literature does not capture adequately insights from international applications of modularization through the supply chain. Thirdly, aside from Pan et al. (2012), the impact of modularization across project phases has not been fully explored and articulated.

This research work intends to address these concerns by identifying and classifying a range of modules from an international spread of projects. In doing so, it provides insights into how construction companies are applying modularity concepts across project phases, and gives a more comprehensive account of what is meant by a module. The authors also reflect on how practitioners may utilize the insights. Their proposition is that, firstly, the definitions of a module should reflect project phases, and secondly, a richer model for understanding modularization can be developed, which takes into account both preassembly options and product architecture hierarchy. Modules can be plotted on these dimensions to take a more informed and systems-based approach to modularization. Hence, the main issue addressed is, in the context of different phases of a building project, *what is a module*? This question, as the authors will show, is indeed much more complicated than initially seems the case. In addressing this question, this paper empirically investigates the use of modularity in 15 different construction projects situated in Italy, Germany, Brazil, and the United Kingdom. Breaking down the research question, the following aims are specified:

- To understand perceptions and definitions of modules from different perspectives;
- To identify categories of modules across different projects, analyzing how they are used in relation to product architecture and degree of off-site manufacture; and
- To develop a framework for practitioners to consider modularity across the project phases.

Literature Review

Modularization in Construction Projects

As previously noted, in the context of the construction industry, there are substantial variations in the definitions used. Table 1 underlines this issue and shows that definitions refer to different aspects of modularity. It also highlights that definitions of a module are sparse within the construction engineering and management literature. There is a difference between a module and a broader view of modularity (Miller 1998). Doran and Giannakis (2011) provide a more extended definition of construction modularity to include a modular approach to design, production, and planning. Indeed, modularity can be considered as having a time dimension that changes throughout the phases of a project (Pan et al. 2012). The latter argue that the overall off-site strategy should be integrated across project phases.

Elsewhere, researchers analyze modularity by focusing on the degree of component independence and interface standardization (Voordijk et al. 2006). Modular houses have been characterized as being made up of modular units, built off-site with connections to adjacent units that are completed on site, including the use of standardized interfaces (Hofman et al. 2009).

There are international examples of studies giving empirical insight, which help shape a new understanding of modularization. Barlow et al. (2003), while analyzing the Japanese construction industry, noticed that many companies offer customized buildings coming from preassembled modular units to increase product personalization without incurring costs that are too high or lead times that are too long. Halman et al. (2008) explore the opportunities and limitations of modular approaches in the Dutch house-building industry, concluding that policy changes are also required to support the uptake of modular construction. They further argue of the need to integrate product architecture and supply chain to ensure appropriate alignment. Naim and Barlow (2003) state that standard housing tends to dominate in the U.K. house-building industry, but that innovative approaches could help balance standardization and customization requirements. Further international discussion of modular concepts in buildings is documented in Germany (Schoenwitz et al. 2012) and Sweden (Jonsson and Rudberg 2014). In the United States, the main driving forces for such approaches were found to be time compression and to compensate for the effect of incremental weather conditions (Lu 2009), and there have been studies seeking to promote the productivity of off-site approaches (Eastman and Sacks 2008).

The *off-site* school of thought also has powerful links with modularity (O'Connor et al. 2014). However, the extent to which a component or building system should be produced off-site is a contested issue (Blismas et al. 2006). Perceptions of off-site approaches are also not always positive (Pan et al. 2007; Zhai et al. 2014). The economic factors behind the decision to move activity off-site are complex, and in some cases can be more costly than on-site practices (Polat et al. 2006). Further, various degrees of off-site activity are possible, and these must be linked with various supply chain approaches (Vrijhoef and Koskela 2000). Classifications of

Table 1. Table of Definitions

Definition	Focus	Author(s)
"One of a set of separate parts or units that can be joined together to make a machine, a piece of furniture, a building, etc."	Generic definition of modularity	OALD (2014)
"A module is an essential and self-contained functional unit relative to the product of which it is part. The module has, relative to a system definition, standardized interfaces and interactions that allow composition of products by combination."	Generic definition of a module	Miller (1998)
"Modular systems are composed of elements, or 'modules,' that independently perform distinctive functions."	Generic definition of a modular system	Pil and Cohen (2006)
"Contains the specifications of a building block and interfaces, as well as considerable functionality compared to the end product."	The properties of a construction module	Björnfot and Stehn (2004)
"The provision of modular solutions constructed off site using modular principles and delivered, installed and commissioned on-site to a pre-determined modular plan."	Modular principles applied in construction	Doran and Giannakis (2011)

off-site and preassembly are pertinent to the debate on the application of modularity in construction projects. Gibb and Isack (2003), for example, identify factory-made components and subassemblies, nonvolumetric preassembly, which do not create usable space, volumetric preassembly (fully finished usable space), and modular buildings, which form the structure of the building.

In recent years the role of modularity has received increasing attention in the literature regarding supply chain management (Salvador et al. 2002), where modular approaches have the potential to reduce risk and uncertainty through the supply chain (Gosling et al. 2013a). Some of the few studies on the topic (Doran and Giannakis 2011; Hofman et al. 2009; Voordijk et al. 2006) report that the supply chains of modular housing systems are made up of two kinds of actors: (1) the system architect and integrator, who defines the product architecture and the design rules for the new modular building; and (2) module suppliers.

Modularization and Product Architecture

Modularity is a strategy for efficiently organizing complex processes and products. In general terms, a modular system is composed by modules that are "loosely coupled" (Mikkola 2006; Schilling 2000) and that can be "mixed and matched" (Schilling 2000) thanks to standardized interfaces (Baldwin and Clark 2000). The concept of modularity has been applied to, among the others, products, organizations and supply chains (Pero et al. 2010). Products can be either *modular* or *integral* depending on the allocation of functions to modules (Ulrich 1995) and on the nature and number of interfaces (Ishii et al. 1995). In a pure modular architecture each module performs only one function and interfaces are standard. Product modularity allows firms to increase product variety while reducing the adverse impacts on operational performance coming from product proliferation.

Modularity research can be considered over a range of disciplinary levels, including design theory and operations management (Salvador et al. 2002). Moreover, modularity has been found to be a significant design variable in helping align design and supply chain processes (Pero et al. 2010). From the design perspective, a commonly discussed root to modularity is through standardized product platforms and definition of modules through the product architecture (Baldwin and Clark 2000; Hofman et al. 2009; Ulrich 1995). This might include the mapping of relationships between design elements, the use of design rules to establish functions and system boundaries, as well as establishing rules for interfaces between elements (Baldwin and Clark 2000). O'Connor et al. (2015) have shown that combining design standardization with modularization can lead to benefits that exceed the additive sum. From the operations management perspective, modularity has largely been considered as a strategy to increase commonality across different product variants within a product family without incurring in operational inefficiencies (Salvador et al. 2002). Schoenwitz et al. (2012) take more hierarchical view of modular product architecture, clustering house elements into categories, components, and subcomponents. In their study, they highlight the different levels of choice at these hierarchical levels.

This paper is built on the hierarchical structure highlighted in Schoenwitz et al. (2012). Such formal articulation of product architecture is relatively rare in the construction sector, but it has been shown to be a powerful way of developing modular design principles across industries (Baldwin and Clark 2000; Ethiraj and Levinthal 2004). Schoenwitz et al. (2012) suggest that the hierarchical structure within the context of a house can be composed of subcomponents, components, and building elements. Subcomponents are the lowest level defined in this study: they are likely to be used by other areas within a building, either at component or element level and they can be fully or partially assembled off site and often require to be integrated with bigger building elements. Beams and pillars are good examples of this category. Components are fully or partially finished building elements that form part of larger structural elements assembled on site. Wall, floor, and roof elements are good examples of this category. Building elements are likely to represent large repeatable segments that repeat across a development: they have a structure and can stand alone, and can be the main chunks of which a development project is composed of. Building elements may also create usable space that, in most of the cases, is completely finished in the factory. They are normally connected to a specific function, e.g., entrance or bedroom.

Modularization of Product, Process, and Supply Chain

Fine (2000) considers the many different connections between the product, process, and the design of the supply chain: product design is divided into activities of architectural choices and detailed design choices whereas process design is divided into the development of processes and manufacturing systems. Supply chain design is defined as the activity concerned with supply chain architecture and logistics/coordination system decisions (e.g., Cigolini et al. 2014). These different dimensions must work together efficiently and effectively to meet customer needs (Ellram et al. 2007; Fine 2000).

The definitions provided in the foregoing section explicitly relate to product architecture concerns, but—according to other studies outlined in the literature review—process considerations are closely linked (e.g., Naim and Barlow 2003; Doran and Giannakis 2011; Pero et al. 2015). Vjoordik et al. (2006) apply Fine's model in the context of the construction industry: they provide further insight into product, process, and supply chain alignment in a construction context. They argue that the latter is important for establishing the conditions for the application of modular networks. This paper is primarily concerned with product (product architecture) and process (off-site or on-site), but the discussion to follow shows that the three areas are very closely intertwined and the supply chain will often be involved in modularization efforts.

Research Methodology

Conceptual Development

Building on the concepts outlined in the foregoing literature review, Fig. 1 is proposed to guide the investigation and analschoysis presented in this paper. It was developed based on the following knowledge grounded in the existing literature. First of all, a module can be utilized at different levels of the product architecture, namely subcomponent, component, or element (Hofman et al. 2009; Mikkola 2006; Schoenwitz et al. 2012; Ulrich 1995). Then, modules can be primarily manufactured *off-site* in a controlled environment, but the degree of on-site assembly can vary from a lot of assembly work to very little. In the latter scenario, modules are fitted together using standard interfaces on site (Blismas et al. 2006; Pan et al. 2012; Vrijhoef and Koskela 2000). Finally, modules may be volumetric or *flat pack*. In the former scenario, modules are preassembled to the extent that so that they form usable space before they are delivered to the construction site (Gibb and Isack 2003).

In summary, based on the literature, modularity seems to be utilized at different levels within the product architecture. Each module then can be engineered to tend toward more activities performed, either off-site or on-site.

By combining Gibb and Isack (2003) with Schoenwitz et al. (2012), four different strategies are proposed for the use of modules

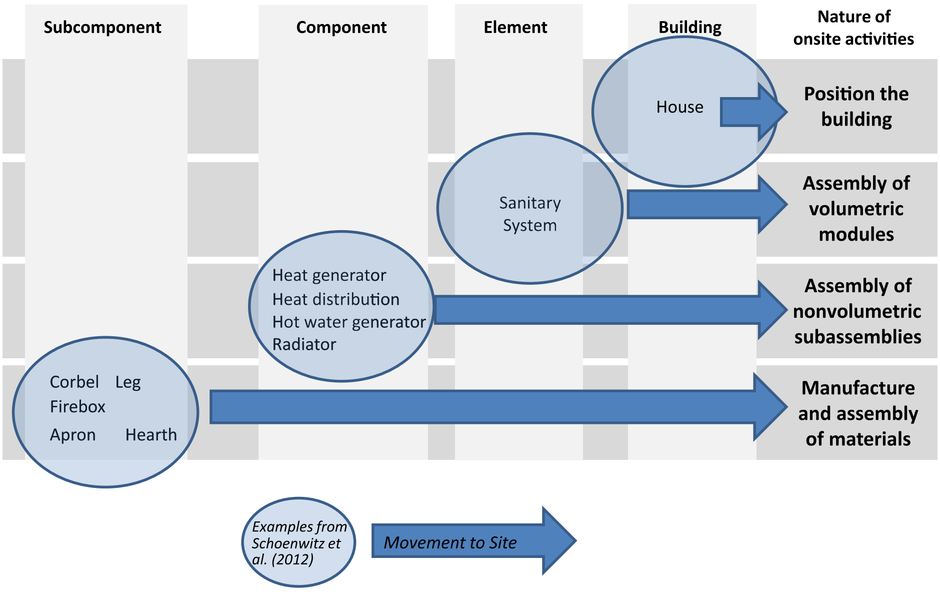


Fig. 1. Potential strategies for modularization of a building at different levels

to guide the paper and empirical work undertaken. These are illustrated in Fig. 1. Gibb and Isack (2003) is a well-established model of the different types of preassembly strategies applicable, but it does not take account of the product architecture and hierarchy, which is presented in detail in Schoenwitz et al. (2012). By combining the two, a richer model for understanding modularization can be developed. The strategies in Fig. 1 are based around the hierarchical levels, so subcomponent, component, element, or building levels can all be used to employ modules. This product architecture is important to understand the complexity of the product design. Furthermore, it is determined how many components are involved and how these work together.

In Fig. 1 the arrows highlight the movement to site and the circles give examples for the appropriate strategy. According to the first strategy, the entire building is fully modularized and somehow transported on-site, where it has to be merely positioned. Under the second strategy, a number of volumetric modules are manufactured off-site, while the assembly phase takes place on-site. As an example, Schoenwitz et al. (2012) mention the sanitary system, which essentially is an installation wall with all the necessary sanitary preinstallation. The third strategy differs from the second one in that here modules are represented by nonvolumetric units: they are manufactured in a factory and then assembled on site. Examples for this strategy are radiators or heat generators, which are nonvolumetric and need to be assembled on site. The fourth and last strategy corresponds to the traditional building approach where bricks and mortar are taken on site. Examples for this strategy (apart from brick and mortar) include corbels, aprons, and legs. The level utilized has implications for the nature of on-site activities undertaken. The empirical work, presented later in the paper, seeks to give further insight into these four different strategies.

Overview of Research Design

Case study research is undertaken in this investigation with the intention of theory building rather than theory testing. Meredith (1998) argues that one strength of case research is that phenomena can be studied in their natural setting, to develop meaningful, relevant theory, generated from understanding gained through observing actual practice. Flyvberg (2006) notes that formal generalization is overvalued as a source of scientific development, whereas "the force of example" is underestimated. This study is intended to give insight into modularization by the latter approach: a distinction is made between projects and modules as different units of analysis. Companies may be working on many projects at a particular point in time. Projects in turn, may be made up of many modules. The primary focus of this research is on the module, attempting to understand the characteristics and use, but a case is described herein as a project (Yin 2003).

Hence, a multiple-case study design is adopted, where 15 projects are investigated in total. This includes embedded units of analysis, which in this study are the 32 modules identified and analyzed. This design helps to achieve depth through case studies, and increased breadth through the embedded units of analysis (Towill et al. 2002). Data were collected through an interview protocol, combining structured and semistructured elements, documentary analysis, and site visits. The approach was chosen in order to allow the authors to probe the complex use of modules in projects, while also maintaining consistency across different cases.

Interview Protocol and Case Selection

The interview script (see Table S1 in the Supplemental Data) was split into a number of headings, which included: company overview and modularization, project specific details, modules used on the project, processes and supply chain, project phases, production details, and performance. Interviewees with either a general operations oversight, or architects were targeted. These specific areas of expertise were targeted due to the foregoing discussion highlighting that modularity is of particular interest to design theory and operations management (Salvador et al. 2002). Interviewees, therefore, constituted a mixture of managing directors, designers and architects, technical directors and project managers. This allowed for a more rounded view of the interpretation of a module.

Follow-up e-mails and photos of particular modules were often exchanged following each interview. In some cases, early drafts of the diagrams presented in this paper were used to prompt discussion throughout an interview. Data collection also included, where possible, site tours. Four of these were conducted in total. Archival data, such as websites, project descriptions, architectural drawings, and project management plans, were also reviewed to get a deeper understanding of each of the projects. To anchor the questions in the interview protocol, interviewees were encouraged to pick a specific project to focus on. An overview of the project details, as well as the analyzed modules included in the study, are shown in Table 2, along with the type of interviewee associated with each. In total, the modular approaches in 15 construction projects are investigated.

Case studies should be selected with a good sense of purpose (Stake 1994). This study sought cases that offer "useful variation on dimensions of theoretical interest" (Seawright and Gerring 2008). Achieving maximum variance across relevant dimensions has stronger claims to representativeness than other case selection methods, because efforts are made to include coverage of a particular categorization. Case studies should also be selected based on both literal replication technique (e.g., projects with the same modular approach to construction), in order to get convergent results, and the theoretical replication technique, to explore different practices in terms of modularity (Yin 1984).

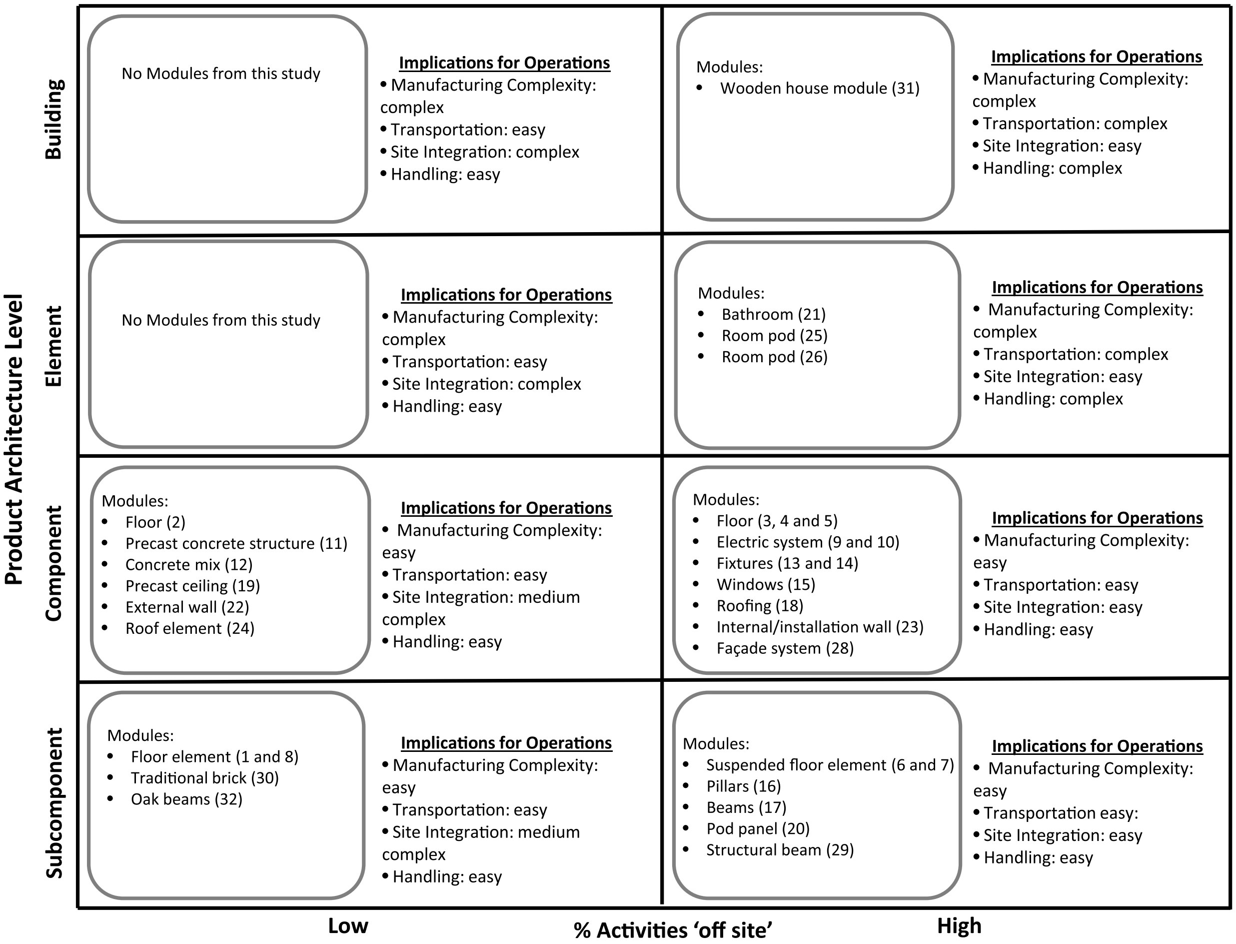
In particular, replication technique was used to, firstly, understand perceptions and definitions of modules from different perspectives and project phases, and secondly, to analyze how they are used in relation to product architecture and degree of off-site manufacture.

Based on the guidance from Yin (1984), Stake (1994), and Seawright and Gerring (2008), case study sampling and selection were based on the criteria developed as follows:

- First, relevance, purpose, and motivation (Stake 1994): the purpose of this study was to investigate the application of modularization. Hence, projects were targeted with the belief that they would further refine the understanding of modular approaches. Case study companies' known interest in modular techniques, and practicalities such as the willingness of interviewees to participate proactively in a research program were also considered;
- Second, fit with theoretical dimensions (Seawright and Gerring 2008): cases were selected to cover the classification of the

Table 2. Overview of Research Methods, Projects, and Module Information

Module	Definition	Design approach	Module level	Project	Project description	Value (€/$, mn)	Location
1	Floor element	Modular	Subcomponent	9	Shopping mall	5/6.6	Italy
2	Floor	Traditional	Component	8	Three residential buildings for 44 apartments	4.5/5.9	Italy
3	Floor	Traditional	Component	13	One building with 7 floors	11.5/15.2	Italy
4	Floor	Modular	Component	10	Two buildings for industrial use and one office tower	3.6/4.7	Italy
5	Floor	Traditional	Component	11	One building with shops and 40 apartments	8/10.5	Italy
6	Floor element (susp.)	Modular	Subcomponent	12	Hotel	17/22.5	Italy
7	Floor element (susp.)	Modular	Subcomponent	1	Office with 3 floors	7/9.25	Italy
8	Floor element	Traditional	Subcomponent	8	Three residential buildings for 44 apartments	4.5/5.9	Italy
9	Electric system	Traditional	Component	13	One building with 7 floors	11.5/15.2	Italy
10	Electric system	Traditional	Component	11	One building with shops and 40 apartments	8/10.5	Italy
11	Precast concrete structure	Traditional	Component	13	One building with 7 floors	11.5/15.2	Italy
12	Concrete mix	Modular	Component	1	Office with 3 floors	7/9.25	Italy
13	Fixtures	Traditional	Component	11	One building with shops and 40 apartments	8/10.5	Italy
14	Fixtures	Modular	Component	12	Hotel	17/22.5	Italy
15	Windows	Traditional	Component	8	Three residential buildings for 44 apartments	4.5/5.9	Italy
16	Pillars	Modular	Subcomponent	9	Shopping mall	5/6.6	Italy
17	Beams	Modular	Subcomponent	9	Shopping mall	5/6.6	Italy
18	Roofing	Modular	Component	10	Two buildings for industrial use and one office tower	3.6/4.7	Italy
19	Precast ceiling	Modular	Component	1	Office with 3 floors	7/9.25	Italy
20	Pod panel	Modular	Subcomponent	10	Two buildings for industrial use and one office tower	3.6/4.7	Italy
21	Bathroom	Modular	Element	12	Hotel	17/22.5	Italy
22	External wall	Modular	Component	5	Luxury residential house	0.75/0.99	Germany
23	Internal/installation wall	Modular	Component	5	Luxury residential house	0.75/0.99	Germany
24	Roof elements	Modular	Component	5	Luxury residential house	0.75/0.99	Germany
25	Room pod	Modular	Element	7	94 terraced house development	13.7/18	U.K.
26	Room pod	Modular	Element	15	Students hall of residence	30.7/36.84	U.K.
27	Precast concrete block	Traditional	Subcomponent	2	Two residential towers: 14 floors	8.5/11.23	Brazil
28	Facade system	Modular	Component	14	Office and residential scheme	3.6/4.8	Italy
29	Structural beam	Modular	Subcomponent	14	Office and residential scheme	3.6/4.8	Italy
30	Traditional brick	Traditional	Subcomponent	3	Two residential towers: 18 and 24 floors	N.A.	Brazil
31	Wooden house module	Modular	Building	4	Temporary wooden structure house	1/1.3	Italy
32	Oak beams	Traditional	Subcomponent	6	Residential oak beam house	0.5/0.66	U.K.



Product Architecture Level	Low: Modules	Low: Implications for Operations	High: Modules	High: Implications for Operations
Building	No Modules from this study	• Manufacturing Complexity: complex • Transportation: easy • Site Integration: complex • Handling: easy	Modules: • Wooden house module (31)	• Manufacturing Complexity: complex • Transportation: complex • Site Integration: easy • Handling: complex
Element	No Modules from this study	• Manufacturing Complexity: complex • Transportation: easy • Site Integration: complex • Handling: easy	Modules: • Bathroom (21) • Room pod (25) • Room pod (26)	• Manufacturing Complexity: complex • Transportation: complex • Site Integration: easy • Handling: complex
Component	Modules: • Floor (2) • Precast concrete structure (11) • Concrete mix (12) • Precast ceiling (19) • External wall (22) • Roof element (24)	• Manufacturing Complexity: easy • Transportation: easy • Site Integration: medium complex • Handling: easy	Modules: • Floor (3, 4 and 5) • Electric system (9 and 10) • Fixtures (13 and 14) • Windows (15) • Roofing (18) • Internal/installation wall (23) • Façade system (28)	• Manufacturing Complexity: easy • Transportation: easy • Site Integration: easy • Handling: easy
Subcomponent	Modules: • Floor element (1 and 8) • Traditional brick (30) • Oak beams (32)	• Manufacturing Complexity: easy • Transportation: easy • Site Integration: medium complex • Handling: easy	Modules: • Suspended floor element (6 and 7) • Pillars (16) • Beams (17) • Pod panel (20) • Structural beam (29)	• Manufacturing Complexity: easy • Transportation easy: • Site Integration: easy • Handling: easy

Fig. 2. Matrix for analyzing modules

strategies for modularization shown in Fig. 1, as well as the categories emerging from Fig. 2, so that projects and modules utilized different strategies. The extent of off-site and on-site was a secondary dimension. Hence, cases repeated across categories of interest; and

- Third, geographical and market sector scope: to learn across national boundaries, diversity was also pursued in geographical location of the projects and in the business sector. The case studies are situated in Italy, Germany, Brazil, and the United Kingdom, helping give a good international spread of projects. Furthermore, to be more specific and focused, this study focused on building projects only, primarily in the residential sector, while also commercial buildings are included in the sample.

As part of the interview protocol, interviewees were asked to discuss projects they have been involved with, according to suitability and link with modularity. Construct and external validity, and reliability were ensured in the data collection by the use of the study protocol shown in the supplemental data, the use of multiple sources of evidence, and in the research design by the use of replication techniques.

Identifying and Analyzing Modules

After specific projects were identified and discussed, interviewees were then encouraged to describe the product architecture and design. Questions probed the level of predefinition, perception of levels within the product architecture, bill of materials, product and material *families*, and modules within the project. Once this general information was discussed, interviewees were prompted to describe the project phases, the approach used in designing and assembling, as well as the managerial challenges encountered along the project. Then, the interviewees were asked to focus on the most important modules for the project they had chosen.

Depth of information for a module was emphasized over breadth (i.e., the number of modules). This often triggered a wide-ranging discussion of the definition of a module. Modules that had been identified were then probed in more detail, including questions related to repeatability and the percentage of off-site versus on-site preassembly. Information gathered through interviews and secondary sources has been categorized and contextualized (e.g., Miles and Huberman 1984). These steps allowed for cross-comparison of projects, module characteristics and strategies, which are presented in the findings.

Results and Analysis

Modularity across Project Phases

By combining the generic project phases suggested by Pan et al. (2012) and Kagioglou et al. (2000), and mapping on some direct quotations from the empirical work embedded in this study, different views on modularity emerge also from case studies, as shown in Table 3.

Table 3 highlights that in the early phases of the project (i.e., during planning and design phase), modularity is perceived as

Table 3. Meaning of Modularity across Project Phases

	Project phase			
Crosscutting themes	Planning and design phase	Preconstruction phase	Construction phase	Postconstruction phase
Interpretation of modularity	"The client can configure the office mixing and matching 12 repeatable module spaces" (Project 1) "There are design-related modules: the size and layout of the apartments (2, 3 or 4 rooms). These are defined during design phase." (Project 13)	"Modularity allows you to use the modules on various projects geographically distant, just configure interfaces in order to standardize them." (Project 4) "A design can be broken down into 3 levels: primary, secondary and attributes" (Project 6)	"There are modules that are completely precasted and then transported into the building, e.g., bathrooms." (Project 12)	"Modularity of electrical systems facilitates maintenance" (Project 1) "Modularity provides flexibility in the later life cycle of the building as the layout can be adapted. It also facilitates maintenance." (Project 14)
	"Design starts with a grid made of squares of 150 cm^2" (Project 14)	"There are many modules in the building, at different levels." (Project 8)	"There are modules that are made up of parts that arrive in site and are built, e.g., electric system." (Project 12)	
Summary of meaning	Grid layout product architecture	Align hierarchy level with supply chain	Physical manifestation of modules	Flexibility in use
Modularity related issue	Extent of standardization	Understanding different building levels	Organizing production off-site and assembly on-site	Ease of maintenance and reconfiguration

a concept related to the division of space and the repetition of spaces. It is strongly associated to a design supported by a *grid*, where elements within the grid repeat. In the preconstruction process (i.e., the second phase of the process), when the engineering of the project takes place, the focus is on the product architecture and hierarchy: it means decomposing and detailing the elements that will compose the grid. When it comes to construction (i.e., the next phase of the process), modularity takes a physical meaning, in that it is associated to off-site and precast, and to how it can reduce the complexity of the work to be done on site. Finally, in the postconstruction phase, modularity is perceived to be useful for making easy maintenance, as well as to be leveraged for reconfigure the building.

To add further clarity to Table 3, a modular design is distinguished from a traditional design: a modular design typically starts with a grid to divide up the space for construction. The designer then employs a systems view within this grid, where consideration is given to the interconnections and repeatability of physical items within this grid. This may result in large standard segments that are repeated across a project. This approach is contrasted with a more traditional view in Table 4. From the empirical work undertaken, nine of the projects were classified as having a modular design, whereas six of the projects were classified as having traditional designs.

Table 4. Comparison of Modular and Traditional Designs

Modular design approach	Traditional design approach
Grid layout with repeatable spaces	Limited repetitions of spaces
Design of the building as a system rather than a collection of parts	Building is seen as a collection of individual parts
Consideration of interfaces to make easier the assembly and then the reconfiguration of the building	Definition of interfaces are left open
Consideration of repetition and standardization	Limited standardization
Example Projects from cases 1, 4, 5, 7, 9, 10, 12, 14, and 15	Example Projects from cases 2, 3, 6, 8, 11, and 13

For example, Project 7 is a residential development situated in the United Kingdom designed to provide high-performance units for a low build cost, using modern methods of off-site manufacture. The development offers 94 new homes arranged in a modern interpretation of a classic Victorian terrace. The accommodation ranges from one-bedroom flats to four-bedroom houses, appealing to a variety of users. The scheme was designed from four segments that repeat, allowing for significant use of standard modules and interfaces across these segments.

A further project (see Project 14) is a redevelopment and construction of corporate headquarters in Milan (Italy), including two residential towers. The offices are divided into two main buildings over nine floors, and the towers contain 100 apartments. The scheme was designed based on 1.2 m grids, which repeat throughout the building. The designers used the grid to take into particular consideration the installation of preassembled elements without the use of traditional external scaffolding, as well as including modular design layouts.

Project 1 is a three-floor office situated in northern Italy. Architects divided the building, supported by the grid, into spaces, e.g., offices and bathrooms, whose position and internal design were to be detailed and organized with client's (a real estate company) support, respecting the constraints given by the position of the pillars.

Physical Utilization of Modules

Fig. 2 shows the 32 modules classified according to the level of off-site activity (where a high level corresponds to more than 50% done off-site) and the product hierarchy level. By looking closer at Fig. 2, the majority of modules (22 out of 32) have a high level of off-site activity. Only one module was identified at the building level in the product hierarchy. Three are at the element level, and the majority are at the component or subcomponent level (respectively 17 and 11 modules). There are no examples of modules with low level of off-site activity at the building and element levels of the product hierarchy.

All modules at building and element level are part of modular design systems, while all the other cells of the matrix contain both modular and traditional designs. Furthermore, when comparing the percentage of off-site activities performed for each module, at the lower levels of the product architecture, the importance of off-site activity appears independent from the design approach (i.e., traditional versus modular). The design approach and level of off-site are reconciled at the high levels of the product architecture, as—at least according to this study—a modular design approach is always associated with high off-site.

However, one of the most surprising results is that the design approach is not aligned to the percentage of off-site: both Modules 27 and 30 are part of traditional design strategies, but with remarkably different off-site activities. Therefore, there is a misalignment between the design approach and the percentage of off-site activities. The bigger the module is the higher is the probability that this will result in off-site manufacturing methods being applied.

Modularity at Different Product Architecture Levels

Modular designs may be operationalized at the building level, i.e., at the highest level in the product hierarchy. This strategy will likely make use of volumetric methods of construction. For example, Module 31 (Table 2 for full information) from Project 4 illustrates an example of low-cost houses for people whose houses have been temporarily destroyed or temporarily occupied for security reasons after an earthquake. The design exploits a modular wooden structure with volumetric approach to enable the building to be moved if required. The whole building, in this case, is a module and is almost completely built off-site, quickly and on a low-cost basis. Transporting the whole building and accommodating late change are difficult in such approaches, though.

Modular designs may also be operationalized at an element level. This strategy is well illustrated by the use of studio pods in Project 15. This is a student hall accommodation development in London. The scheme will result in 418 self-contained student accommodation units, plus leisure and retail space spread over three new buildings. A typical studio has an area of 17.4 m† and provides self-contained accommodation offering bathroom, kitchen, study, and sleeping areas. The scheme was designed to be constructed via modular bedroom *pods* (module 26 in Table 2). The studio pods will form three separate student accommodation blocks of between four and nine stories. This affords opportunities for lead-time reduction and repeated spaces across the scheme. Sequencing, in terms of regular and ordered delivery patterns, as well as transporting large volumetric elements is challenging to manage.

As mentioned previously, Project 14 is a redevelopment and construction of corporate headquarters in Milan, including two residential towers. This project makes use of modular designs operationalized at the component level. The scheme was designed to take into particular consideration the installation of preassembled elements. In particular, Module 28 (Table 2) refers to the units composing the outer skin of the office façade, which has been preassembled in the factory. Delivery times have been able to be reduced by using a construction solution that allowed high-speed installation while ensuring a guaranteed high quality of the installed product. A challenge of this strategy is that there is a large upfront investment of resources in the engineering and design process with the risk that it may not be used on a further project. Hence, this is dependent on the scale of the project and the repetitions of the module within the project. Further, interconnections between different modules must be effectively managed.

The final strategy for operationalizing modular designs takes place at subcomponent level. Project 10 is the development of two buildings for industrial use and one tower for offices. The project was designed using a modular approach, but no volumetric elements were shipped on site to build it. Suppliers provided the main precasted components and subcomponents to be assembled on-site to form the building structure and, among them, the pod to cover the rooms of the building for industrial use (Module 20 in Table 2). The pods were fixed on the structure with easy-to-remove interfaces (e.g., bolts).

Traditional Designs at Different Product Architecture Levels

From this study, no modules using traditional designs were identified at building or element levels. The first strategy for traditional designs, therefore, is to operationalize them at the component level. Project 13 refers to the building of a building for residential use in Sardinia (Italy). It has seven floors, plus two levels underground for garages and cellars. The design and the construction of the building followed traditional approach. Clients could customize each apartment, deciding for instance the position of walls, the kind of floors, and sanitary arrangements. Floors were built using precasted elements brought on-site during the building process (Module 3 in Table 2).

Traditional designs may also be operationalized at subcomponent level. Project 2 is a development of two residential buildings in the countryside of Brazil, built in structural masonry. It consists of 96 apartments, divided in two towers of 14 floors each. Project 3 is also located in Brazil, and is a development of two residential buildings in São Paulo. The project develops in total 498 units over 6,400 m^2. The primary construction method is reinforced concrete frame. The project started in May 2013 and was still ongoing at the time of writing. Module 27 refers to a precast concrete block that is produced by external suppliers to be used for assembly on site.

Strengths and Weaknesses of Modules at Different Product Architecture Levels

Fig. 2 also indicates some competitive trade-offs and patterns across the matrix. Toward the top of the matrix, at element and building levels with high levels of off-site manufacture, transport and handling become a major issue. According to one of the interviewees from project 1: "the transport is a critical matter: truck renting is expensive and regulations are strict," while responding to late changes is very difficult because, "there is no possibility to change later in the project." Besides, it is also likely that "the customer is only involved early in the project to define some of the details," as stated by a manger of Project 12, who also believes that the benefits of off-site manufacture can be realized, given that "the benefits of using precasted element is a reduction of lead time."

Toward the bottom of the matrix, a different strength and weakness profile is evident. Extensive use of subcomponents can markedly increase the complexity of site management, meaning that "managing a large set of suppliers is a challenging issue for us," as stated by a team member of Project 2. This can sometimes result in the need for external help and analysis, as happened in Project 3 where "there is a high need of coordinating the work in the yard, so we hired a consultant to help us." Even at the component level, managing interconnections between components can be an issue. For example, Project 8 required "periodic meetings between the suppliers and the general contractor" that were "held every week to coordinate the work in the yard and assure maximum safety." Using component and subcomponent-based strategies does offer

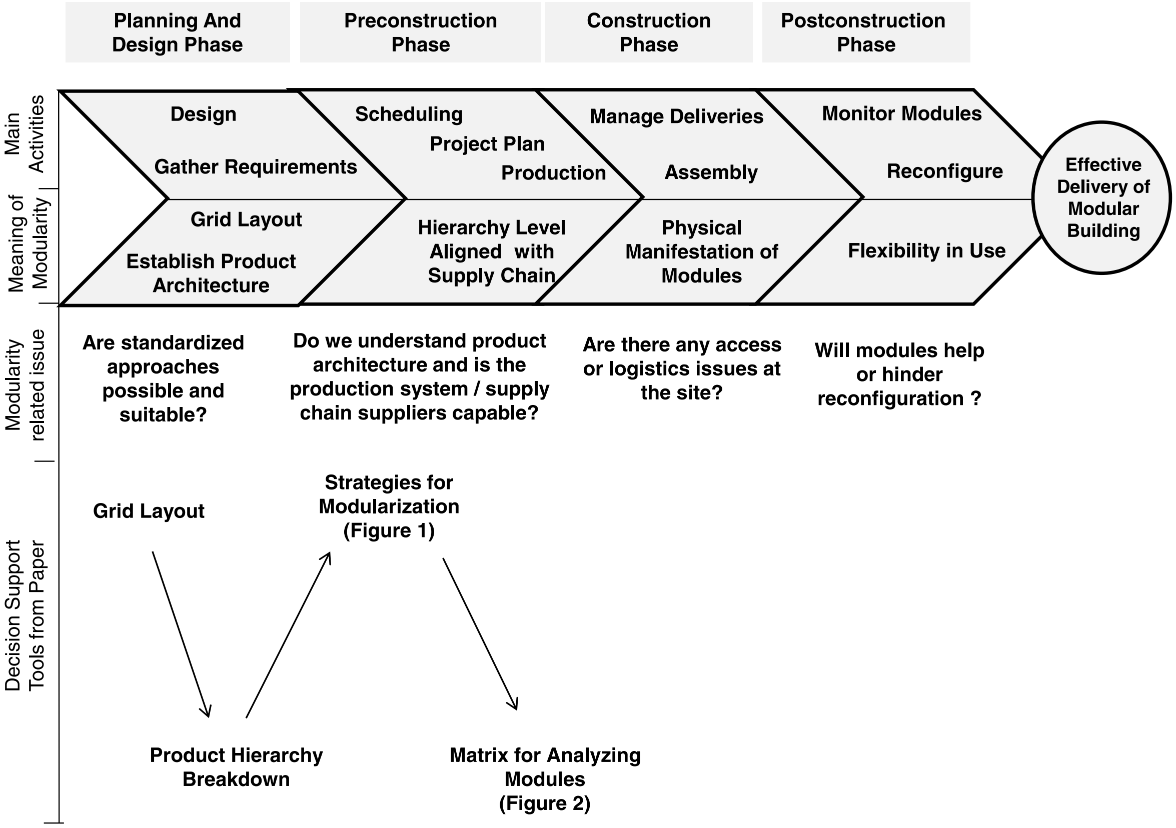


Fig. 3. Modularity and different phases in project lifecycle

potential flexibility and adaptability to late client changes on site, if required.

Such quotes illustrate some of the trade-offs in relation to strengths and weaknesses of different positions, echoing themes within the literature. For instance, Cigolini and Castellano (2002) find that modularization improves safety and quality at the expenses of a more complex handling and logistics. Cost considerations and time saving estimates remain the main key factors for evaluating the overall effectiveness of modular methods.

Practical Guide for Implementation

Fig. 3 brings together different elements of the paper to develop a practical guide for practitioners to follow. It is organized using general project phases, and the following recommendations are developed for practitioners, which link to different parts of this paper.

First, use a grid layout to support planning and design phase. This supports repeatability and standardization in the design stage and later in the project phases.

Second, develop a formalized product architecture to support design choices. This advice builds on general design guidelines by Ulrich (1995), but also extends the product hierarchy of a building system proposed by Schoenwitz et al. (2012).

Third, link the product architecture to the four strategies (reported in Fig. 1) in the preconstruction phase to establish the level at which they will be used. This helps establish a physical delivery strategy for the modules.

Fourth, operationalize the strategy through the planning matrix (Fig. 2) in the preconstruction stage, where the costs and benefits of different approaches can be considered and analyzed.

These recommendations also require the evaluation of inputs, drivers, and constraints. This helps in the formulation of an appropriate strategy for the project. In the figure, these are depicted as required inputs and constrain considerations. Fig. 3 also highlights the need to think across project phases, including the integration of design, purchasing, and site operations. The analysis of perceptions of modularity at the different levels lends support to the distinction between design theory view and an operations management view of modularity, and the importance of uniting these different perspectives. This also supports the findings of Pan et al. (2012), highlighting the need for collaborative working between designers and site/operations early in the project lifecycle, along with feedback from manufacturers to give insight into off-site possibilities, as offering the best opportunity for the benefits of modularization to be realized. Finally, a systems thinking mind-set is encouraged, based on the principles outlined in Gosling et al. (2013b) in the approach to modular construction, since it is important to consider the whole, and the role of modules and actors within it.

Conclusions

This paper has considered the question of *what is a module* in the context of different phases of a building project. The main aims of this paper were to understand perceptions and definitions of modules from different perspectives, identify categories of modules across different projects, and analyze how they are used in relation to product architecture and degree of off-site manufacture. The final aim was to develop a framework for practitioners to consider modularity across the project phases. In addressing these aims, the paper gives insight into the nature of modularity in housebuilding projects, showing at the same time the complexity and the opportunities for applying it in the construction industry.

The first aim was to understand perceptions and definitions of modules from different perspectives. A design-based and an operations-based perspective of modularity has been identified. Integrating these perspectives offers the best opportunity for exploiting the benefits of modularization. Indeed, design can help set a *path* to modular construction by encouraging the use of repeatable spaces and a systemwide view of the ways elements and components are intertwined, thus allowing leveraging of modularization with e.g., off-site production and reconfiguration in the postconstruction phase.

Next, the aims were to identify categories of modules across different projects and analyze how they are used in relation to product architecture and degree of off-site manufacture. Based on evidence from 15 projects situated in Italy, Germany, Brazil, and the United Kingdom and 32 *practitioner defined* identified across the projects. Using the design approach and the level at which modules are operationalized, eight strategies to use modules can be theoretically envisaged: six of them are also supported by evidence collected over the fieldwork on case studies. Multiple strategies are likely to be employed across a specific project, as some portions of a building are designed and operationalized at element level, whereas other portions are operationalized at subcomponent level.

Addressing the final aim, the paper also developed a guide, with insight from practice, to help organize project activities for effective modularization. The guide, for each project step, proposes the main activities to perform in each project phase, along with required inputs and key question to address. Thus, it can be used as decision support system for both architects and site managers to jointly consider modularization strategies. Finally, specific support tools are proposed for each project phase. These tools refer to a structured four-step approach (Fig. 3) to be followed to consider both modular design and off-site strategy: (1) use a grid to support both planning and design phase; (2) formalize product architecture; (3) define the level of off-site for each element in the product architecture; and (4) consider implications for operations (Fig. 2) of each decision by trading-off costs and benefits.

At the beginning of the paper the authors posed the question, in the context of different phases of a building project, *What is a module*? This paper captures the meanings, perceptions, and definitions of modules across a project lifecycle, and eventually proposes the following unifying definition of *a module* in building projects, which the authors articulate as “A module is physically manifested as a construction unit that is part of a wider system, which can be integrated through preplanned interfaces. These physical modules are the result of, and can facilitate, modularization in different phases of the project. They may be considered at different hierarchical levels within the overall product architecture, may be manufactured on or off-site, and can be volumetric or nonvolumetric.” This definition helps enlarge the debate about, and the practitioners’ perception of modularity to include both design and operations perspectives, with a system-thinking approach.

The overall contribution of this article has been to help arrive at a more comprehensive definition of a module through the project phases, drawing on insight from a range of international building projects. The guiding frameworks developed help to organize our thinking in relation to potential modularization strategies. The case study elements of the paper are based on building project, largely in the residential and commercial sector. Projects were selected based on the closeness of fit with the study, and modules were self-selected by interviewees. Care should therefore be taken in generalizing the findings, and the scope is limited to building projects. Although these generalizability issues do exist, the authors consider that the models, definitions, and categories developed can be used and adapted by practitioners to articulate their modularization strategies, and researchers may build on them via wider-scale testing. The actual cost analysis for each strategy, and the combinations, provide an interesting avenue for future research. The template proposed also requires greater testing with a wider range of modules across different projects and sectors.

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Supplemental Data

Table S1 is available online in the ASCE Library (www.ascelibrary.org).

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