Architectural Intelligence

RESEARCH ARTICLE

Open Access

The PreDI matrix-a common terminology for offsite construction: definition, verification, and demonstration in environmental impact studies

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Abstract

Given the increasing interest in offsite construction and the prefabricated components it produces, this paper aims to establish a common matrix, the PreDI, for the offsite construction industry. The effort is to enhance the comparability of research and practices in offsite construction, making it more universally understood. Offsite construction involves manufacturing components in a factory and then assembling them on-site. It is considered a more sustainable approach due to less material usage, energy consumption, and waste generation during component fabrication. However, the lack of common terminology for offsite construction poses many challenges in the industry and its research, hindering communication and research.

The Prefabricated Dimensions and Integrations (PreDI) matrix, developed in the study, provides a solution for industry and research use. Thus, industry and academia can utilize the PreDI widely, accurately, and precisely in communication. This paper demonstrates the PreDI matrix's application in life cycle assessment research on offsite construction, showcasing its utility and setting the stage for more robust research analyses in the future. Using the PreDI matrix in 24 U.S. Department of Energy Solar Decathlon houses further highlights its potential in the industry. Finally, the paper concludes with a broader outlook on its impacts on offsite construction.

Keywords Offsite construction, Prefabrication, Common terminology, Life cycle assessment

1 Introduction

Despite numerous advancements in the Architecture, Engineering, and Construction (AEC) industry, the building sector is a major contributor to annual energy usage and greenhouse gas emissions within the United States. Considering the cumulative effects of material extraction, material waste, construction machinery, operational energy, and demolition, every building has significant environmental impacts during construction and operation. Currently, traditional onsite construction continues to be the dominant construction method. An alternative, offsite construction, is an industrialized and manufactured-style approach by which building components (e.g., roofs, walls, floors) are manufactured in a facility with a controlled environment and transported to the construction site to be conjoined into a functioning building. Offsite construction has many benefits: schedule improvements, quality control, worker safety, less material usage, low construction waste, short construction time, and low greenhouse gas emissions due to the reduced use of labor, transportation, and onsite machinery. Extensive research has been conducted to

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understand/quantify the benefits of offsite construction compared to traditional onsite construction methods.

Offsite construction has a longstanding history in the U.S., dating back to the 1920s. Yet, its broad acceptance has been constrained by its complex contextual nature, closely tied to social, economic, and environmental factors. Consequently, a universally applicable terminology has yet to emerge, given the diverse sectors involved, such as manufacturing, architecture, engineering, construction, and regulatory frameworks (U.S. Department of Housing and Urban Development, 2023). The research on offsite construction primarily emphasizes manufacturing like prefabrication, precast concrete, and modular construction, while aspects of operation, process, and sustainability receive comparatively less attention. Additionally, there is little or no cross-fertilization between research areas, the researchers themselves, and the research institutions (Hosseini et al., 2018). There is a crucial need for a consistent and compatible common language to facilitate dialogue, debate, and the exchange of ideas and initiatives between academia and industry. This paper aims to address this challenge by establishing a common terminology matrix to define the types and features of offsite construction clearly. The framework will enable researchers and engineers to enhance their understanding and contribution to improving offsite construction practices.

First, this paper dives into the history of offsite construction and its re-emergence in the United States building industry. Then, the paper focuses on a literature review to identify the need for common terminology. The PreDI matrix is then introduced as the common terminology for offsite construction. The demonstration of the use of PreDI is shown in the following section to enhance the applicable understanding of offsite construction components and their types. Next, the PreDI matrix is used for the life cycle assessment (LCA) for a Solar Decathlon house to compare the environmental impacts of different offsite construction methods. The LCA studies demonstrate that the PreDI matrix can significantly clarify the differences and improve the understanding of research analyses. The PreDI matrix is a well-organized common terminology for offsite construction and is ready for wide use in academics and industry.

2 Offsite construction industry

Offsite construction uses a controlled environment to fabricate subassemblies such as walls, roofs, doors, and even bathrooms, all then assembled on-site. Despite the numerous advantages associated with offsite construction, from its emergence to today, its market share has been very low—about 5% (Razkenari et al., 2020; Maximize Market Research Pvt Ltd., 2023)—due to many challenges. These challenges include regulatory barriers, financing gaps, supply chain disruptions, workflow obstacles, factory pipeline inconsistencies, cultural and social barriers, and transportation complications. Offsite construction has continuously captured the attention of researchers and engineers, actively studying ways to unlock its potential benefits for our economy, environment, and society.

While offsite construction applies to various building materials, including concrete, steel, and wood, since the early twentieth century, timber structures have been predominantly the most developed form in offsite construction in the US, and proliferated as a wartime necessity for fast-built, demountable, mass-quantity military housing. Multiple prominent prefabricated house manufacturers, including Sears Homes and National Homes Corporation, emerged during that time. Sears Homes shipped "mail order" prefabricated kits-to-parts to buyers who assembled their houses independently or with externally contracted builders until the 1940s. National Homes Corporation, using sheet materials (Bruce & Sandbank, 1972), adopted an approach that is more reflective of the contemporary landscape of prefabricated housing in the US, making it the focus of a more detailed study.

Unlike traditional construction, which gradually evolved over centuries, the offsite construction industry developed rapidly in a highly competitive climate, hindering widespread collaborative standardization. With all the lessons learned from throughout the 1900s, including from other small but innovative housing manufacturers, the construction industry in the U.S. is now currently experiencing another wave of factory-built prefabricated houses. Offsite construction has shifted away from mass-built catalog single-family residences towards bespoke constructions and multi-unit complexes, including high-rise buildings.

3 The literature review on common language for offsite construction

Over a century, as offsite construction evolves, its terminologies and classifications are continuously developed to match. Off-site construction has undergone various terminological and taxonomic evolutions (Goulding 2019) due to its diverse levels of prefabrication, ranging from individual parts to panelized, volumetric, and complete structures. Both industry and academia have employed numerous taxonomies and terminologies in discussing offsite construction, leading to blurred distinctions between different systems (Ginigaddara, 2021). Gibb (2001) initially introduced terms such as component manufacture and sub-assembly, non-volumetric preassembly, volumetric pre-assembly, and modular/complete building, which were subsequently adopted by various researchers to align with their research objectives. Another classification, "Dimension," was used to categorize off-site construction into components, panels, and modules (Quale, 2012; Boyd, 2013; Lawson, 2014; Gusmao, 2023). The concept of structure has been pivotal in describing offsite construction, with terms such as frame systems, open/closed panelized, block work, hybrid, non-structural volumetric, and structural volumetric spaces (Kamar, 2011; Steinhardt, 2016; Abanda, 2017; NHBC, 2018; Agapiou, 2021). Many existing classifications are rooted in industry practices and theoretical assumptions rather than systematic evaluations, often lacking in defining distinct features. Recently, the International Code Council (ICC) took a significant step towards standardizing terminology by releasing new insights on offsite construction, considering various system functions such as structure, enclosure, finishes, mechanical/electrical/plumbing services (MEP), etc. (ICC/MBI, 2021). However, to this day, the persistence of outdated and non-standardized terminology across the industry and supply chain has created a new disorganized state.

The various terms used in academic research reflect current terminology's chaotic, unstandardized, and sometimes contradictory condition. The absence of standardized vocabulary impedes the meaningful comparison of case studies and the drawing of conclusive insights. The following two examples in the existing literature highlight ambiguities in available vocabulary.

In one comparative study on carbon emissions between traditional onsite and modular construction (Kouhirostami & Chini, 2022), the authors provide insights into general trends based on seven case studies. However, a notable limitation arises from the authors' universal labeling of all prefabricated components as "modular," despite the inclusion of at least three distinct types of prefabricated assemblies in their studies. These include (1) a three-dimensional volumetric prefabricated house (Pervez et al., 2021), (2) a "semi-prefabricated" precast/in situ hybrid building (Mao et al., 2013), and (3) an "offsite panelized modular" building (Monahan & Powell, 2011). The authors' decision to treat all cases under the broad term "modular" stems from a lack of common terminology across the sources. However, this approach overlooks significant differences in construction methods and materials, undermining the study's ability to draw conclusive insights on the environmental impacts of building construction.

The U.S. Department of Housing and Urban Development (HUD) has established offsite construction definitions in 2023 (HUD, 2023). However, it needs more precision to distinguish these degrees into their accurate classifications. For example, the "2D Open Panel" offsite construction system leaves intentional ambiguity in the description, stating that the components that fall into this category "may be sheathed on one side in light-frame construction" (HUD, 2023, p.11). Though perhaps a small difference, adding a single face importantly reflects significant changes in manufacturing and construction processes. To integrate the sheathing of the 2D panel into offsite manufacturing production lines, more working steps with unique materials and equipment may be necessary. Suppose the sheathing on one side of a 2D Open Panel wall assembly includes architectural weather barriers and a façade. In that case, the construction might have a shorter onsite timeline before watertightness is achieved than if those barriers and façade had to be installed onsite. HUD acknowledges the need of common terminology as they underscored the importance of establishing a standardized terminology for offsite construction in their research roadmap (HUD, 2023).

The ability to quickly process the complexities of a construction system and its implications would allow for an expedient, reliable approach to exchanging information, straightforward communication among different trades, and trustable data and comparison analysis between distinct types of offsite construction. Thus, as new and established construction companies re-embrace offsite construction, common terminology is crucial for developing and advancing offsite construction in the industry and academics. A universal terminology in offsite construction also makes future advancements in data infrastructure for the AEC industry possible, potentially bringing a leap in the current building information system for the AEC industry.

4 The PreDI matrix for offsite construction

To facilitate widespread acceptance and adaptation by both industry practitioners and academia, the Prefabricated Dimensions and Integrations (PreDI) matrix of common terminology for offsite construction has been developed by Washington University in St. Louis to clarify industry practice and academic research in 2020. The PreDI aims to integrate existing terminologies, encompassing those referenced in the literature (Sect. 2.2) and recent developments like ICC/MBI (2021) and HUD (2023), into a comprehensive and universal framework. The PreDI matrix identifies different prefabricated assemblies based on 1) their perceived dimension (degree of offsite construction) and 2) different subsystems integrated into the prefabrication. The subsystems include structural, architectural, interior, mechanical, electrical, and plumbing engineering (MEP) systems. Every prefabricated assembly is identified first by its perceived dimension, followed by its integrated subsystems.

The dimensions of offsite construction are divided into three types: 1-dimensional (1D), 2-dimensional (2D), and 3-dimensional (3D) according to the prefabricated components. The levels of dimensions are meaningful in defining prefabricated components due to impacts on the manufacturing steps, product transportation, onsite assembly process, material, and waste flows, engineering services, permitting, inspection, and other services.

1) 1D prefabricated components are linear members/assemblies and can be thought of as existing along a line (though they may operate with loads in multiple dimensions). They refer to precut individual structural members, including beams, columns, joists, studs, boards, window and door casements, gable ends, etc. Solar Decathlon 2015 Clemson University's Indigo Pine house, in Fig. 1, illustrates 1D prefabrication.
2) 2D prefabricated components are planar or "panelized" assemblies – walls, partitions, floors, and ceiling pieces. They primarily operate perceptively in two dimensions, though all have depth/thickness as assemblies of multiple subpieces. They refer to a so-called "panelized system" of different types that can be assembled or installed on-site. The components often arrive as flat-packed labeled panels. 2D prefabricated components can be external-facing walls, floors, internal load-bearing walls, or partitions. They might be open or closed panel systems or other panel types. 2D prefabrication is accessible to transport, lends itself to mass customization, and has infinite configurations. Solar Decathlon China 2018 Washington University in St. Louis's Lotus House, in Fig. 2, illustrates 2D prefabrication.
3) 3D prefabricated components are "volumetric" or "modular" assemblies and often create spatial definitions through structured and enclosed inhabitable areas. 3D prefabricated components generally refer to a three-dimensional structural system combined with other systems or units to form an entire building. 3D components are often referred to as "modular" or "volumetric systems." It can combine different trades to create functional modules like bathrooms, kitchens, and MEP core pods. Solar Decathlon 2015 Missouri University of Science and Technology's Nest Home, in Fig. 3, illustrates 3D prefabrication.

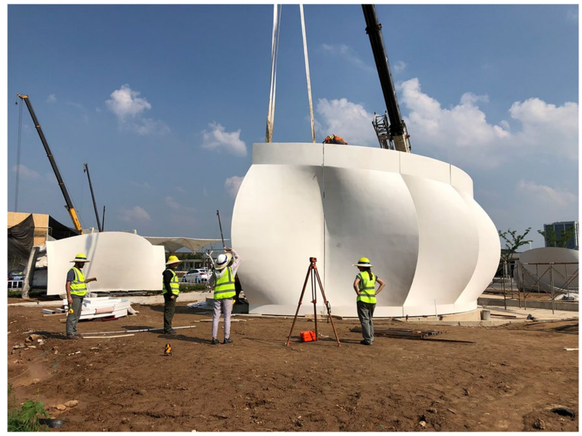

Fig. 2 2D Prefabrication showcase

The integrated subsystems include Structural (S), Architectural (A), Interior (I), and Mechanical Electrical Plumbing Engineering I systems. At least one, but up to all four systems are installed in each prefabricated component in the factory. Other systems may be installed on-site, but the PreDI matrix only classifies prefabricated components based on those installed before leaving the factory. –S - The Structural system includes load-bearing and shear-resisting members, partition structure,

Fig. 1 1D Prefabrication showcase

Fig. 3 3D Prefabrication showcase

connections, etc. –A - The Architectural system includes weather barriers, insulation, exterior finishing, tectonic elements, portals (windows, doors, etc.), and non-load-bearing stabilizing components.

The categorization of prefabricated components into the integrated subsystems contained is important for immediate information exchange about the component to all designers, consultants, builders, and other parties involved in the process of design and construction. The categorization by subsystem also allows different manufacturers with distinct products to define their prefabricated component type with common terminology clearly. Higher offsite construction and subsystem integration levels generally correspond to faster on-site assembly. Hence, the matrix provides a common terminology to enhance design collaboration between architects, interior designers, engineers, and contractors on prefabricated projects.

The PreDI matrix is built with the combinations of pairs of two categories – three different dimensions, and four subsystems. There are a total of 72 potential combination types. Table 1, the PreDI matrix, summarizes 14 common types of offsite construction in current industry practice below.

Table 1 Offsite construction Prefabricated Dimensions and Integrations (PreDI) matrix

Terminology	Subsystem				Description
	Structure	Architecture	Interior	MEP	
1D.S	X				Structure members altered to the required dimensions and forms in the manufacturing factory.
2D.S	X				A 2D structural plane preassembled offsite by two or more structure members without other finishes.
2D.A		X			2D architectural finishes prefabricated offsite
2D.SA	X	X			Two or more structural components and at least one architectural component prefabricated offsite.
2D.SI	X		X		Prefabricated 2D, load-bearing partition walls or floor panels with interior and engineering finishes.
2D.IE			X	X	Prefabricated 2D, non-load-bearing partition walls with interior and Engineering finishes.
2D.SAI	X	X	X		Prefabricated two or more structural components and at least one architectural and one interior component.
2D.SAIE	X	X	X	X	All prefabricated - a constructed structural system and an integrated MEP system closed by architectural and interior panels on either side.
3D.S	X				A connected structural 3D frame, or joists prebuilt offsite
3D.IE			X	X	Various MEP prebuilt systems or pods, including hardware, fittings, associated assemblies, and controls, not distributing pipings and ducts.
3D.SA	X	X			A prefabricated 3D structural frame with architectural elements.
3D.SAI	X	X	X		A prefabricated 3-dimensional structural frame preassembled with architectural and interior elements.
3D.SIE	X		X	X	Preinstalled MEP and engineered system assemblies within a 3D prebuilt structural framing with interior finishes.
3D.SAIE	X	X	X	X	A prebuilt 3D, enclosed structure with all building systems assembled and installed.

All information provided in the PreDI matrix is empirical, based on industry and academia on offsite construction. Many factors may add complexities to the provided definitions – zoning laws, material availability, infrastructure quality, etc., and can limit the implementation of certain levels of offsite construction in various regions. As such, definitions should be considered indicative of industrial availability trends but certainly not comprehensive of all global markets. The detailed descriptions of each are as follows.

1. 1D.S refers to structure members that are altered to the required dimensions and forms in the manufacturing factory. One example is a prefab log frame house in which the structural components are preprocessed to fit together easily onsite. 1D.S offsite constructions are, by definition, cut to size and shape offsite before shipping, but they can also include further modifications like passthrough holes for MEP systems (wires, ventilation ducts, etc.), pre-drilled holes for bolts and other connecting members at designed locations, notches and other related cutouts at connection points. Another example is wood 2×4 members, joined offsite into structural I-beam shapes.
2. 2D.S is made by two or more structural members preassembled offsite to form a two-dimensional plane. Commonly referred to as “open panel” 2D components, 2D.S panels have only the structural components of the plane and do not contain any other finishes or panels. The components arrive on-site pre-sized and assembled to form a space. 2D.S does not include architectural facing components, insulation, interior and mechanical systems because they are easily damaged during transportation. After open panels are erected onsite, other components are added.
3. 2D.A includes two-dimensional architectural finishes, such as completed Insulated Glass Units (IGUs), windows and doors, shading devices, cladding panels of predetermined sizes, shapes, colors, materials, etc. modified to specification.
4. 2D.SA includes two or more structural components and at least one architectural component. All arrive onsite preassembled to form a plane. It is commonly referred to as “single panel” 2D components, as they may have backing on their exterior side but leave an exposed interior side, allowing for installing insulation and MEP systems onsite before interior backing closes the panel. 2D.SA offsite construction allows for MEP systems and insulation to be installed inside the wall during onsite assembly before interior finishing. Cutouts in the panel for onsite portal installation are standard. The exterior panel may already be finished, though not necessarily. It is common for the seams between single-panel constructions to require weather barrier applications before continuous exterior finishing is applied. Unfinished floor and roof cassettes are other common examples of 2D.SA. Wall module exterior-facing single panels may include prefabricated portals such as windows and doors.
5. 2D.SI refers to two-dimensional interior panels, such as customized interior surface panels of different sizes, shapes, and materials to be assembled on-site. It can also include prebuilt cabinetry. 2D.SI includes interior load-bearing walls.
6. 2D.IE prefabrication includes two-dimensional, non-load-bearing partition walls with interior finishes and MEP systems.
7. 2D.SAI prefabrication includes two or more structural components and at least one architectural and one interior component. All arrive onsite preassembled to form a plane. 2D.SAI components are commonly called “closed panel” 2D components, as both sides of the two-dimensional panel have closed backing. MEP is run through designed panel cavities onsite. MEP systems are installed onsite in this case, meaning that this prefabricated panel can have cutouts in the panels/finishes for easy, nondestructive onsite installation of MEP systems. For double-panel systems without MEP systems already installed, insulation is commonly blown into the panel after MEP systems have been installed onsite. Finishes (façades, paints, etc.) may be pre-applied to one or both faces of the panel.
8. 2D.SAIE prefabrication includes a constructed panel system and an integrated MEP system closed by architectural and interior sheets on either side. All arrive onsite preassembled to form a plane. The integrated MEP system is designed in such a way that it connects to the central MEP system of the building during assembly—one example of a 2D.SAIE system integrating into the overall building MEP system is as follows: An interior wall for a bathroom may already have the pipe fittings and systems in place, be closed on both sides and must now connect to the rest of the building. Another example is floor cassettes.
9. 3D.S prefabrication includes a connected structural frame, with joists prebuilt offsite. 3D.S prefabrications may define the structure of only a tiny portion of the whole space or building, requiring multiple 3D components to be assembled to define larger spaces. This can include structural skeletons for other materials to be attached to. This may include

the structural elements for an entire room. 3D.S may also include other structural systems such as racking or decking.

10. 3D.IE includes interior and various MEP system hardware, fittings, associated assemblies, and controls – not including distributing piping and ducts – aggregating to a single centr"l "mechanical c"re" to be placed within the building onsite. Mechanical cores are generally contained within the overall building and can be placed into a building utilizing any level of offsite construction.
11. 3D.SA prefabrication includes a 3-dimensional structural frame with architectural elements. Interiors and insulation remain unfinished so that MEP systems can be run through necessary walls, floors, and ceilings onsite before the module is finished. Multiple modules may be structurally connected before continuous interiors are installed.
12. 3D.SAI prefabrication includes a 3-dimensional structural frame preassembled with architectural and interior elements. The module may not be insulated and may have strategic cutouts for MEP systems to be inserted within the unit onsite before insulation is added.
13. 3D.SIE prefabrication includes preinstalled MEP and engineered system assemblies within a 3-dimensional structural framing with interior finishes. A prefabricated bathroom unit is an excellent example of 3D.SIE approach. This pod assembly always includes a structural frame to support the MEP systems and often includes interior finishes.
14. 3D.SAIE prefabrication includes a 3-dimensional, enclosed modular with all building systems assembled and installed. This approach consists of the structural frame, architectural exteriors, barriers, insulation, and portals; interior finishes, glazing, and built-in fixtures; and MEP system hardware, fittings, and controls properly fitted through necessary spaces to be easily connected to the rest of the 3D.SAIE's MEP design.

All levels of offsite construction outlined above are in isolation, meaning that while they can be and often are combined in construction, for definitions, they are considered as they would appear by themselves. To improve the veracity of the PreDI Matrix, multiple offsite construction companies and projects of varying sizes and manufacturing focuses were consulted for feedback. The PreDI matrix is analyzed further, as it stands, for its applicability in the research/academia and practicing industry fields.

5 Applying the PreDI matrix

As mentioned, offsite construction today is re-emerging into the building industry, as it is largely praised as a more sustainable approach to construction. This field is a primary culprit of annual U.S. carbon emissions (Kamali & Hewage, 2016). Recently, research on offsite construction mainly focuses on attempts to quantify a prefabricated building's total environmental impact, known as Life-Cycle Analysis (LCA). Thus, in this analysis of the applicability of the PreDI matrix to the research and academia fields, the universal terminology of offsite construction will be examined from a comprehensive, existing research publication of a comparative LCA to locate ambiguities the traditional terminology may presume. Then, an LCA analysis is conducted utilizing distinctions offered by the PreDI matrix, and in doing so, standardized, precise terminology proves invaluable for contemporary research.

5.1 Case study 1: An existing LCA comparison of a modular vs. conventional home

The first case study reviewed is D. Kim's publishment of an LCA comparison between Modular and Conventional Housing in Benton Harbor, Michigan, done in collaboration with Redman Homes (Kim, 2008). The comprehensive study aims to analyze the difference in embodied carbon and overall environmental impact between a "modular" and conventional (stick frame) home. Both constructions were 1,456 sq. ft. and of similar overall size, and the modular home was manufactured in a plant 78 miles from its site. The research quantified the material use, embodied energy, embodied carbon emission, and solid waste for the whole building life cycle.

Kim identifies material savings in offsite manufacturing facilities and decreased employee daily transportation to the site as primary contributors to the offsite construction's sharp drop in embodied carbon emissions compared to the conventional construction approach. Kim found that the modular home produced 12,397 kg of embodied carbon emissions compared to the 23,050 kg produced by the conventional home – a 46% reduction. However, due to the lack of standardized terminology within this comprehensive LCA, these found benefits of offsite construction can only be noted for projects like the studied project and manufacturer.

Kim refers to these prefabricated components as "two modules," with Module A containing a "master bedroom, 1 bathroom, kitchen, dining rooms, and utility spaces," while Module B contains "3 bedrooms, 1 bathroom, living room, and stairway." Through this description, it may be implied that the "modules" can be identified as 3D.S, 3D.SA, 3D.SAI, 3D.SIE, or 3D.SAIE components, as the components clearly are prefabricated to create a volume of inhabitable space, and the calculations notably include the structural materials used to build the components. After this, however, the identification of the component's type becomes more arbitrary. The inclusion of Gypsum Board, Fiberglass, and Shingle in the LCA calculations suggests that the components could be 3D.SA, 3D.SAI, or 3D.SAIE types. After this determination, the inclusion of only the Carpet and PVC can intimate the potential inclusion of the Building Engineering and Interior systems.

While this may seem trivial to the calculation, considering Kim's conclusion of the significance of employee daily transportation and material savings could add a wide margin of discrepancy. For example, if no Building Engineering systems had been installed before the prefabricated components were transported to the site, this would increase the employees traveled by at least three (3) contractors (MEP contractors) and the quantity of materials transported to the site. If this hypothetical increase were to be multiplied to a much larger scale, such as a high-rise "modular" building, this increase in carbon emissions could be extensive. Thus, Kim's remarkable findings of a 46% carbon reduction from a conventional home to a modular home become nullified to only represent this project, due to the lack of a standardized terminology to designate Kim's findings.

Furthermore, Kim also found a 9% increase in materials used in offsite construction compared to the conventional approach because each module had to be structurally self-sustained and withstand greater non-standard loads during shipping and craning on site. The result was twofold: more structural material was consumed, and interior walls between modules had to be doubled. Though this finding is significant for Kim's analysis, its impact can vary widely due to a "module's" vague terminology. If the entire Module A or B were to be an identified 3D.SAIE, this increase could be determined simply as a symptom of its transportation method. If however, this Module A was rather split into an inventory of one 3D.SAI, with the engineering systems installed between the doubled interior walls of Modules A and B, this material increase could be a symptom of the designed offsite construction component itself. The implication the latter could then identify is that structural redundancy has the potential to become far worse a problem for multi-story modular buildings in which floors and ceilings are doubled as well. Without a common terminology, this increase in materials associated with structural bolstering for transportation and craning could even be considered an attribute of all prefabricated components, despite seemingly applying exclusively to volumetric (3D) assemblies.

5.2 Case study 2: A performed LCA analysis of Purdue INhome, using the PreDI matrix

In applying the PreDI matrix to further research, a preliminary LCA analysis was performed directly using the defined PreDI matrix to its study. To do so, the INhome, a 984-sf single-family unit, was analyzed due to the extensive data available and for its use of offsite construction. The INhome's design, led by Professor William Hutzel of Purdue University and his students in 2011, won second place in the U.S. Department of Energy's Solar Decathlon Competition. The house is notable for its high efficiency in engineering design, affordability, human comfort, energy performance, renewable energy production, and faithfulness to regional style. The house primarily comprises five 3D volumetric modules (3D.SAIE) for the main structure and 2D prefabricated panels (2D.SAI) for the garage.

A tally LCA model was created based on the as-built Revit model of the INhome, representing the offsite construction approach, and the net total (A1-C4) global warming potential carbon emission was 21,439 kg CO_2. Through examination of the floor plans of the home, seen in Figs. 4 and 5, it is found that an estimated 17% of all walls in the home (including the garage) are redundant (this estimation does not consider ceiling/roof structure and deck structure). Since these components are confirmed as 3D.SAIE prefabricated components, it is noticeable that these redundant walls are intentional and designed for, as the engineering systems are preinstalled inside the walls along with their architectural insulation and interior finishes. Kim's research shows that redundant walls are necessary for each 3D.SAIE assembly to be structurally independent during transportation and installation. Distinguished through the use of standardized terminology in this analysis, it can be understood that rather than a symptom of just this one project, redundant walls are a ubiquitous consequence of 3D.SAIE assemblies. The increased material use in this project, suggests that 3D.SAIE offsite construction consumes at least 2% more material than conventional onsite construction from redundant walls alone, as shown in Fig. 5. Even marginal material use increase may be significant, as material embodied carbon emissions constitute most of the total building emissions – seen as 75% in one comparative analysis (Pervez et al., 2021). Because this increase is attributed to some, but not all, types of prefabricated components, further analysis should be performed on the difference in material use per the types listed in the PreDI matrix.

To make these figures more accurate, further study of transportation-associated embodied carbon (gate-to-site and daily employee transportation to site) (Kouhirostami & Chini, 2022) is necessary compared to discrepancies

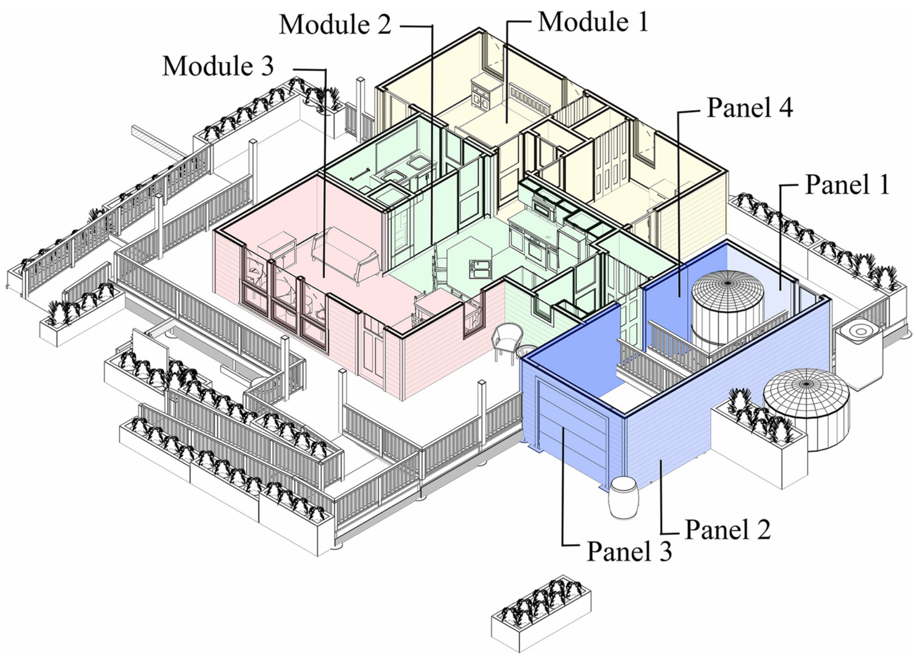

Fig. 4 INhome, a hybrid of modular and panelized system

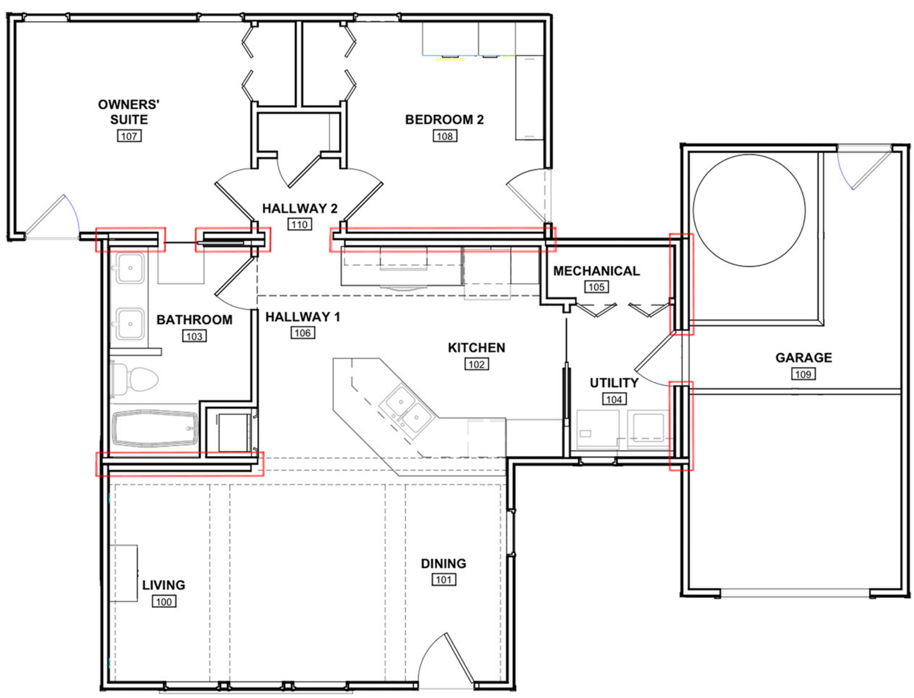

Fig. 5 Simplified floor plan of INhome, Redundant walls circled in red

in dimension and integrated systems within a prefabricated component. The Benton Harbor home in Case Study 1 and Purdue INhoIe in Case Study 2 make valuable steps to quantify the potential of 3D.SAIE and 2D.SA offsite construction to reduce the environmental lifecycle impact of buildings.

Applying PreDI matrix definitions to these ambiguities can clarify the assessment and evaluation of practices and lead to new insights. To further verify the PreDi Matrix, Solar Decathlon homes are used to help identify, challenge, and solidify trends while continuing to demonstrate the applicability of the PreDI matrix. Solar Decathlon homes are generally useful for study because they are well publicly documented, represent future sustainable housing, and are prefabricated. Some are not ideal because they may be designed to be transported great distances to competition sites or may be designed for a combination of competition and permanent site climates. Solar Decathlon homes of interest for their US-based timber-structure 1D, 2D, and 3D construction are listed below as suggestions for analysis (these traits are selected for interest because they should generalize to the United States housing market more accurately than non-timber structure non-US-based homes). For temporal relevancy, only homes competing in the last eleven years are included (except the INhome). In Table 2, 24 selected Solar Decathlon houses use the terminology developed in the PreDI matrix to represent different product delivery approaches of offsite construction technology in various climate zones.

6 The PreDI matrix and industry practice

PreDI offsite construction terminology can be applied to construction processes and the industry models that govern them. Though off-site construction processes differ per manufacturer, the PreDI matrix offers construction terminology suited for all existing off-site construction. The PreDI matrix can help integration-type builders gain greater control over the supply chain and manufacturing process with clarity. PreDI terminology promotes the builder's communications with collaborators, allowing all stakeholders to quickly comprehend the cost, quality, scale, external reliance, and risk of an assembly's manufacturer. Beyond the PreDI terminology's impact on manufacturers and their collaboration between trades, the PreDI terminology also easily communicates distinct requirements and changes for contractors in the construction process. Though the existing terms "panelized" and "modular" may imply some estimates to a contractor, the changes in the systems integrated into these prefabricated components can vary vastly. Instead, the immediate implication of all the trades involved before a component reaches the site through the PreDI matrix allows contractors to instantly have a stronger understanding of the timeline, workflow, and collaborators involved in the installation.

Table 2 PreDI matrix application in 24 solar decathlon houses of different colleges

	Year	Project Name	ProDe Matrix Terminology	Paricipation Colleges
1	2020	Warrier Home	1D.S	University of Waterloo
2	2017	Our H2Ouse	1D.S	University of Californiia, Davis
3	2015	Indigo Pine	1D.S	Clemson University
4	2015	DURAhome	1D.S	New York City College of Technology
5	2015	Reflect Home	1D.S	Sacramento State University
6	2017	Enable House	2D.S	Northwestern University
7	2017	RISE House	2D.S	University of Californiia, Berkley and University of Denver
8	2020	Net Zero Home	2D.SA	Kensas State University
9	2018	Lotus House	2D.SA	Washington Uniiversity in St. Louis
10	2013	PEAK House	2D.SAI	West Virginia University
11	2017	Crete House	2D.SAIE	Washington Uniiversity in St. Louis
12	2020	SPARC House	3D.S	Univ. of Colorado, Boulder
13	2020	Mojave Bloom	3D.S	University of Nevada, Las Vegas
14	2020	ADAPTHAUS	3D.SIE	University of Illinois at Urbana Champaign
15	2013	Radiant House	3D.SAI	Santa Clara University
16	2017	surviv(AL) House	3D.SAIE	University of Alabama Birmingham and Calhoun Community College
17	2015	Nest Home	3D.SAIE	Missouri University of Science and Technology
18	2015	SURE House	3D.SAIE	Stevens Institute of Technology
19	2015	NexusHaus	3D.SAIE	The University of Texas at Austin and Technische Universitat Munchen
20	2015	Aggie Sol	3D.SAIE	Unniversity of California, Davis
21	2013	Phoenix House	3D.SAIE	University of Louisville, Ball State University, and University of Kentucky
22	2013	DALE House	3D.SAIE	Southern California Institute of Architecture and California Institute of Technology
23	2013	Start Home	3D.SAIE	Stanford University
24	2011	INhome	3D.SAIE	Purdue University

To demonstrate the application of the PreDI in effectively specifying the off-site construction to actual practices, 24 Solar Decathlon competition houses over the past 20 years have been used. The Solar Decathlon competition, established in 2002, is a prestigious collegiate competition that challenges teams from around the world to design, build, and operate highly efficient and innovative solar-powered houses. It has fostered interdisciplinary collaboration among students in architecture, engineering, and sustainability-related fields while advancing the development and adoption of renewable energy technologies. Teams are tasked with transporting their pre-designed and prefabricated houses to a competition site, where rapid and efficient assembly is crucial. This necessitates the use of modularity and prefabrication, allowing teams to pre-build significant portions of their houses off-site and then assemble them on-site. The construction methodology employed by Solar Decathlon teams is predominantly off-site construction. The PreDI Matrix is applied to analyze 24 Solar Decathlon houses selected in the past 20 years, evaluating them based on specified dimensions related to their construction techniques. Table 2 summarizes the 24 competition houses, categorized according to the PreDI Matrix dimensions. As shown, the PreDI provides insights into the prevalence and effectiveness of off-site construction methods these teams use.

Firstly, the dimensions indicated by the PreDI matrix provide transparent identification of the construction processes involved in the installation. For instance, the first five houses employed 1D.S off-site construction, which requires minimal off-site assembly and fewer systems integrations. Those houses follow a straightforward Cradle-to-Site model, involving some materials processing, and most building materials are transported to the site in an organized construction workflow. The primary distinction between 1D.S off-site and entirely on-site construction lies in the structural components. In 1D.S off-site construction, components are pre-cut, pre-shaped, and pre-drilled for bolts before shipping, facilitating easy on-site assembly. Prefabricated roof trusses are a significant component of this off-site construction method. Additionally, houses offer flexibility for further modifications, such as passthrough holes for mechanical, electrical, and plumbing (M.E.P.) systems, enhancing adaptability during the final stages of construction.

The next set of six houses, whose PreDI matrix representations contain 2D.S, pre-sized and assembled structural components that form complete sections, such as walls or roofs. Those components typically form a space with multiple functions. For example, Northwestern University's Enable house utilized 6–3/8″ Structural Insulated Panels (SIPs), a type of 2D.S component. These panels offer both rapid assembly and effective thermal insulation. The construction of such components demands more extensive processes and materials for off-site design and fabrication compared to 1D.S components. For houses using 2D components with additional systems like Architecture (2D.SA) and Interior (2D.SAI), the components typically form closed 2D panels, with backing (architectural panel or interior panel) on both sides. However, MEP is run through designed panel cavities onsite, which may require cutouts in the panels/finishes for easy, nondestructive onsite installation of MEP. In cases where MEP systems are enclosed by architectural and interior sheets on either side, the construction is categorized as 2D.SAIE, as seen in the Crete House built by Washington University in St. Louis. This house used two-dimensional insulated precast Ductal wall cassettes, which consisted of 5–1/2″ insulation foam sandwiched between two precast light concrete panels, with the MEP systems embedded within the enclosure of the two panels. These 2D precast Ductal walls were fabricated in a manufacturing facility and subsequently shipped to the competition site for straightforward and rapid assembly.

As indicated in Table 2, numerous teams employed three-dimensional off-site construction, categorized within the 3D group in the PreDI matrix. These teams initially constructed their houses at local sites. For the competition, the houses were disassembled into 3D modules and subsequently reassembled at the competition venue. For instance, the Stevens Institute of Technology team constructed the SURE house incrementally in Hoboken, NJ, encompassing the foundation, floor framing, wall framing, weather protection, insulation, mechanical, electrical, and plumbing (MEP) systems, and floodproofing (SURE Construction, 2015). The completed SURE house was then disassembled into three 3D modules, incorporating all structural, architectural, interior, and MEP components, and transported to the competition site in Irvine, CA (Liberty Science Center, 2024). At this location, the three 3D modules were efficiently reassembled on-site. A similar approach was adopted by other competition teams listed in the 3D.SAIE group. Due to the precise construction requirements of architectural, interior, and MEP components, long-distance shipping poses a risk of damage. Consequently, many teams opted to construct only the 3D structural models off-site, denoted as 3D.S. Other teams incorporated some architectural components into the modules, marked as 3D.SA, or additional interior components, marked as 3D.SAI, as shown in Table 2.

The solar decathlon houses may broaden the definition of off-site construction, as their initial construction did not occur in a manufacturing facility. Nonetheless, the fundamental method of off-site construction remains consistent. The majority of building components are produced off-site—an extended Cradle-to-Gate process—before being shipped as finished or semi-finished components to the construction site for assembly, constituting a Gate-to-Site process.

As illustrated in Table 2, various types of off-site construction involve distinct processes that utilize human and natural resources, resulting in different environmental impacts. Greater precision in terminology will enhance understanding of the nuanced differences between these construction processes.

7 Conclusions

Due to the rapid development of the offsite construction industry in the mid-1900s, and the significant shift from economy-of-scale single-family houses to customized single and multi-unit residences, the existing vocabulary for defining prefabricated assemblies lacks specificity and standardization. This issue is sometimes acknowledged in existing research around offsite construction. Still, a lack of adequate solutions leaves gaps in understanding, making comparisons more difficult to draw and leading to generalizations as misleading proxies for more accurate data. Thus, the PreDI matrix was generated through empirical study, consultation with industry, and cross-checking with markets.

PreDI matrix vocabulary was then applied to existing research. It was demonstrated that research would be easier to draw meaningful conclusions if prefabricated assemblies were more precisely classified than under blanket terms such as "modular" or simply "prefabricated." This application revealed that higher dimensions of offsite construction led to more structural bolstering and material redundancy, leading to more material used (and a potential for higher embodied carbon) compared to lower degrees of offsite construction and traditional construction. It was also revealed that even with an established vocabulary, further steps need to be taken to establish an accepted methodology for the life cycle analysis of prefabricated assemblies, as there is still a considerable margin of error in data generation due to a lack of standardization.

Even without a completely standardized methodology, general trends can be established, challenged, and verified through further studies of prefabricated homes. Solar Decathlon house entries of interest were identified as potential avenues of further study to this end.

Finally, the PreDI matrix vocabulary was applied to vertical integration. By viewing prefabricated assemblies through the lens of a more specific vocabulary, one can understand the vertical integration of subsystems in a manufacturer, as well as the different construction processes that are implied in these varying degrees of vertical integration.

Applying a more specific vocabulary to the current understanding, research, and industry structure of off-site construction allows one to draw more meaningful, nuanced conclusions than with previous terminology sets. By applying the PreDI matrix vocabulary system going forward, research and products can be precisely classified to make communication faster and more accurate. If adopted by researchers and industry professionals alike, the offsite construction industry can reach a level of standardization that allows for collective growth through greater understanding.

Acknowledgements
The research team consulted with Mr. Scott Reichensperger of MiTek Inc. and Mr. Brian Kerkhoff of KA Components.

Authors' contributions
Hongxi Yin: research supervisor and project management; Kaden Chaudhary: draft preparation and revision; Annika Pan: draft preparation and revision; Ming Qu: draft preparation and revision; Cindy Wang: graph preparation; David Yi: table content draft preparation.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
There are no financial or non-financial interests related to this work submitted for publication.
The authors Hongxi Yin and Ming Qu are guest editors of this issue Solar Houses, and Hongxi Yin is a member of Editorial Board for Architectural Intelligence. They were not involved in the journal's review, or any decisions, related to this submission.

Received: 13 February 2024 Accepted: 9 July 2024
Published online: 03 September 2024

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