Design for industrialized construction in architecture education: a case study integrating dfma and digital twin in the design studio

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ABSTRACT: *This case study aims to contribute to the adoption of Industrialized Construction (IC) principles into teaching. The paper presents the work done in a Master of Architecture studio conducted remotely. A pedagogical approach to introduce Design for Manufacturing and Assembly (DfMA) and Digital Twin concepts is presented. An analysis is conducted to evaluate the effectiveness in integrating IC principles into the design studio. The analysis framework uses the DfMA guidelines developed by the American Institute of Architects (AIA), the Royal Institute of British Architects' RIBA Plan of Work 2020, and the British Ministry of Housing's Modern Methods of Construction. The case study uses three phases in the design process, pre-design, design, and post-design, in its evaluation. The analysis results show that certain components of DfMA can successfully be integrated into a design studio framework. Although the structure of AIA and RIBA guidelines is followed, the order of the design process can vary according to the workflow designed by the students in the pre-design phase. The case study demonstrates a pervasive sense of social and ecological responsibility associated with the adoption of IC techniques in the design studio. There is an opportunity to expand the potential of IC practices by thinking beyond the design methodology. Findings suggest modularity as a social connector, which in turn, serves as a component towards a more cohesive built environment.*

Keywords: Education, Industrialized Construction, Design for Manufacturing and Assembly, Digital Twin, Modular Architecture, Built Environment

INTRODUCTION

This paper presents a case study where a design studio explores two concepts of Industrialized Construction (IC): Design for Manufacturing and Assembly (DfMA) and the Digital Twin (DT). The case study involves a design studio conducted as a two-semester course conducted remotely during the 2020-2021 academic year. This was at a critical moment during the world pandemic when there was uncertainty as to the near future of the architecture professional landscape.

Industrialized Construction (IC) describes changes in the Architecture, Engineering, and Construction (AEC) industry driven by the automation and connectivity of industrial and manufacturing practices. There are various components to Industrialized construction, including DfMA for offsite construction and building delivery optimization, and DT for analysis, monitoring, and decision-making. DfMA combines techniques of Design for Manufacturing and Design for Assembly that have been utilized in other industries and applies them to the modularization and offsite production of building components. DfMA techniques focus on reducing the cost and time in the production of building components and are currently integrated into the building production process for residential construction and other parts of the industry where buildings can be easily modularized and mass-produced. Digital Twin refers to the data connection or monitoring of a physical building system using an intelligent virtual representation. DT leverages the technological advances in cloud-enabled tools and platforms for storing, sharing, and management of building information throughout the building lifecycle. It is a modeling strategy that enables project stakeholders to create a digital version of the real system to evaluate scenarios and collect data to make decisions.

CASE STUDY: STUDIO 812

The challenge of introducing IC concepts in the architecture design studio is centered on how to present this paradigm shift to novice designers, with varying levels of understanding of building assembly techniques and processes, and proficiency in computational design and Building Information Modeling (BIM). Eight projects were developed in an architecture design studio during the academic year from Fall 2020 to Spring 2021. The eight projects were designed by students studying in their last year of the Master of Architecture program. Having completed all requirements for the accredited professional degree, the design studios at that level of the program focus on special topics, in this case introducing students to industrialized construction concepts. The initial brief worked as a dynamic document providing an outline for the project. The class was conducted with a design research approach, where students reviewed precedents to become familiar with the state of the art, developed a research proposal in which research questions are identified, and developed a design solution as a speculative project.

Research Proposal

In the first task of the studio, students were given lectures to introduce theoretical concepts and design computing workshops to level their technical skills. Students conducted precedent research to further familiarize themselves with the concepts of DfMA and DT. As part of the research students, students selected one or more architectural design precedents, “reverse engineer” the building systems, and develop a proposal for the building program for their project, and a preliminary prototype.

Design and Modeling

The second task of the project extends from the fall to the spring semesters and involves two design iterations. In the first iteration students focus on the modeling by selecting to emphasize a focus on the DfMA as a smart kit of parts, or DT as a tool for environmental analysis. In the second iteration, students are asked to reflect on the bigger challenges of social and environmental justice and use this lens to revise and develop their projects. This aspect was influenced by complementary lectures related to the current global challenges and issues, such as climate change and health.

FRAMEWORK FOR INDUSTRIALIZED CONSTRUCTION ANALYSIS

To evaluate the effectiveness of integrating industrialized construction principles in the design studio, two sets of documentations were used: the DfMA guidelines developed by the American Institute of Architects, AIA, and the Plan of Work guidelines offered by The Royal Institute of British Architects, RIBA. The Plan of Work recommends a complementary manuscript called MMC: Modern Methods of Construction developed by the British Ministry of Housing, Communities & Local Government Group. For the purposes of this study, it was considered that MMC forms part of RIBA’s guidelines.

Both AIA and RIBA guidelines are organized into three design phases: named pre-design, design, and post-design. Each phase is integrated by subphases to shift from traditional-design practices to industrialized-design practices. The guidelines agree that the pre-design phase can serve as a formal preparation in which the design team and the owner work together on a project's brief. The importance of making the brief, relies on settling a strategy toward the usage of an industrialized construction method in the project. Details regarding the budget of the project, local permitting requirements, construction codes, manufacturer characteristics and initial design considerations must be established. When the pre-design phase is completed, the design phase is ready to put the brief into practice. Although AIA and RIBA differ in the quantity of subphases within each phase, the number depends on the coordination of all the parties involved in the manufacture and design processes. AIA suggests a design freeze subphase to accelerate the coordination and delivery of the project on-site. RIBA suggests that the conceptual design settling, assures that coordination. Once all the concerned parties have accomplished their coordination objectives and outcomes, the post-design phase can be started. This last phase includes the delivery, assembly and installation of the project or project’s components on-site.

Pre-design phase

The aims of the pre-design phase are: to establish the aims of the project itself, to settle the requirements of the client and to define the role of the design team in the project. The outcome of this phase is a strategic brief that includes the planning scheme to be developed in the design and post-design phases. This brief must serve as an agreement between the client and the design team of the project, and it is also an engagement plan with the industrialized construction methodology. In addition, the brief includes a workflow map as a guideline toward the design and post-design phases.

Design phase

The aim of the design phase is to evolve from the initial brief to the technical design, as well as coordinating the design under a ‘manufacturer thinking.’ According to AIA and RIBA, the design phase can consider the following general scenarios: designing for off-site pre-manufacturing, designing for near-site pre-manufacturing, and/or designing for a site-based process improvement. AIA and RIBA agree that the design phase is the longest phase of the IC methodology because it involves an integrated process compound by multiple design decisions. These decisions can be organized in different categories, AIA suggest two categories: the volumetric construction design and the non-volumetric construction design. While RIBA, suggests reviewing the MMC definition framework and its seven categories for manufacturing and assembly practices. The seven categories are: 3D primary structural systems, 2D primary structural systems, non-systemized primary structure, additive manufacturing, non-structural assemblies and sub-assemblies, improvements of traditional building products, and on site-process improvement.

Post-design phase

The post-design phase refers to the handover of the project. Thus, it requires the preparation and delivery of the project or the project's components on site. These include transportation, staging and assembly strategies. And also, a post-assembly vision of the performance of the project. RIBA suggests including post occupancy evaluation tactics, as well as providing formats and tools for keeping track of the building's performance regarding its operations and maintenance.

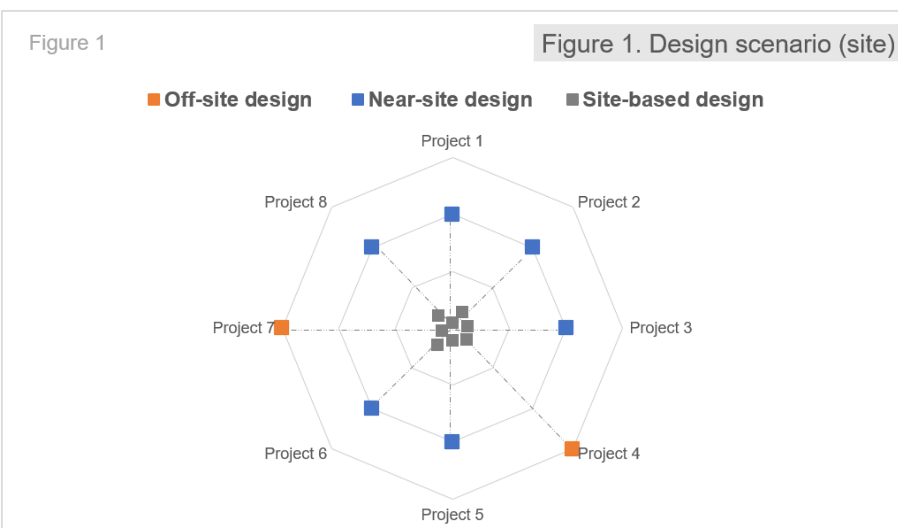
COMPARATIVE ANALYSIS

The 3 design phases are considered in the comparative analysis. The outcome of the 3 phases developed by each project is retrieved in the Studio 812 documentation available online1. The results of the analysis can be classified in the following topics: site as design scenario (Figure 1), general design considerations and categories for design decisions (Figure 2), and subphases used in the design phase (Figure 3). This topic classification is obtained from comparing the modular approaches described in AIA and RIBA guidelines (refer to Figure 0 located in the appendix).

For the purposes of the case study evaluation, it is considered that to accomplish the pre-design phase, students should demonstrate engagement with a topic through research. Thus, each project considers a topic definition, historical precedents of the selected topic, and the translation of those precedents into a contemporary and industrialized context. The design phase is composed of an architectural proposal obtained from the theoretical framework of DfMA, digital twin, and design for modularity. For evaluating the general design considerations of the eight projects, the categories provided by AIA and RIBA's Modern Methods of Construction (MMC) were considered as complementary. For each guideline, the suggested categories are different; AIA focuses on assembly strategies, whilst MMC refers to the components of the project. Finally, the post-design phase is evaluated as a set of recommendations for manufacture, site preparation, and transport staging.

Site as a Design Scenario

As it can be seen in Figure 1, six projects are influenced by a near-site design, while only two projects are shaped by an off-site design. There are no projects considering a 100% site-based design. However, the eight projects relied on traditional practices on site (to a certain extent) for specific moments in the construction of the project itself. For example, some of the projects considered foundations built on-site, carpentry work on-site, and colocation of building components on-site. This situation was part of the final discussions in the classroom because it supports the idea that automation does not necessarily "erase" human labor from construction practices. The discussion included the recognition of the possible design paths to study while implementing an industrialized construction methodology. It is considered that this is an asset for preparing professionals with deeper insights in IC.



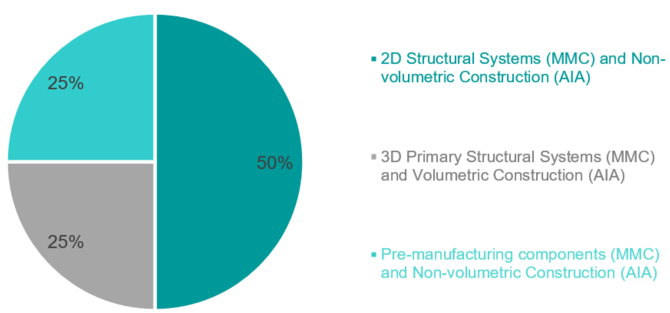
Categories for design decisions

Each student selected the design topic to address in their project. Therefore, eight topics were developed under an industrialized construction methodology: Project 1 focused on Tectonic Aggregations for DfMA

Construction, Project 2 focused on Affordable Housing, Project 3 focused on Modular Systems with Bamboo, Project 4 focused on Design for Automation, Project 5 focused on DfMA for Residential Construction, Project 6 focused on Vernacular Architecture and Carbon Emissions, Project 7 focused on Modular Adaptation for Housing, and Project 8 focused on Harnessing the Wind in Buildings. The variety of topics addressed on each project, confirms the versatile character that the methodology can provide in architectural projects. The selected topics also demonstrate a strong sense of ecological, technological and social responsibility.
Figure 2 shows a proposal to categorize the projects into three categories, which are: 2D Structural Systems (MMC) and Non-volumetric Construction (AIA), 3D Primary Structural Systems (MMC) and Volumetric Construction (AIA), and Pre-manufacturing components (MMC) and Non-volumetric Construction (AIA). These categories illustrate how AIA, RIBA, and MMC can contribute to classifying the implications of industrialized construction in architectural design. The projects demonstrate the application of industrialized construction practices. Pre fabrication, additive manufacturing, robotics, big data, and the internet of things, are evident tools of architectural design in the student projects.

Figure 2

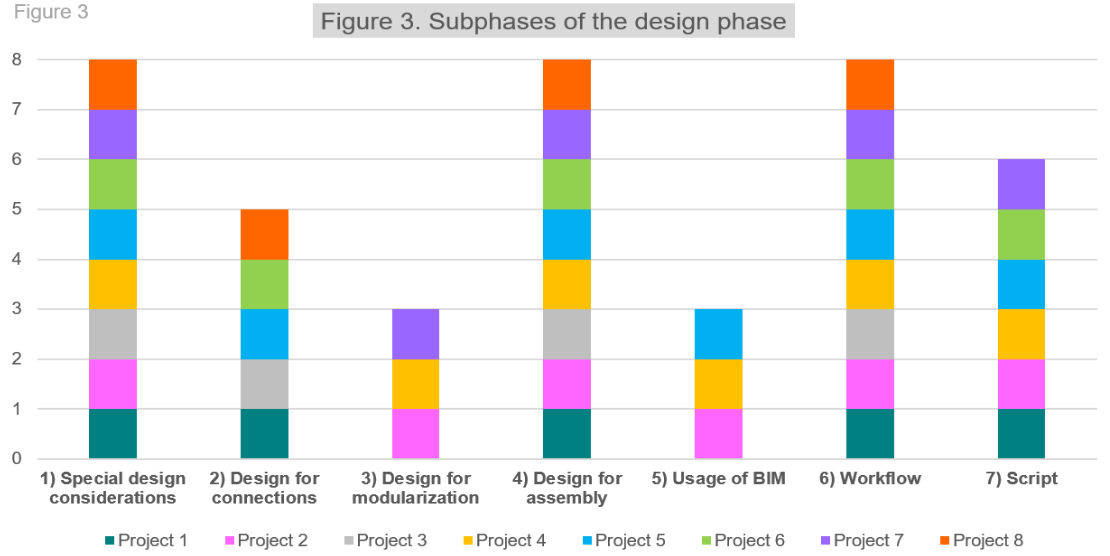
Figure 2. Categories for design decisions



Subphases of Design

This section of the evaluation includes seven aspects of the design subphases retrieved from the AIA and RIBA guidelines (refer to Figure 0 in the appendix to better visualize all subphases). The seven aspects are the following: 1) Special design considerations (geometric design, parametric tools and/or collaborating with the manufacturer), 2) Design for connections, 3) Design for modularization, 4) Design for assembly, 5) Usage of BIM, 6) Settling a workflow and 7) Creation of a script. Figure 3 shows how these aspects are integrated. All projects demonstrate special design considerations, design for assembly, and settling a workflow. The usage of BIM and Digital Twin were more difficult to integrate in the design process due to the lack of foundational knowledge in modeling and simulation. Designing for connections and modularization were also challenging aspects to achieve simultaneously. Projects focusing on design connections did not develop modularization strategies.

Figure 3



DISCUSSION

In this case study, all of the student projects successfully followed an industrialized construction process. The use of the AIA and RIBA guidelines, and the pre-design, design and post-design phases provided insightful evaluation of the case study's integration of Industrialized Construction concepts. This study recognizes the flexibility embedded in the AIA and RIBA guidelines. It was found that the order of the design process can vary according to the workflow developed by the students during the pre-design phase. In addition, the eight projects addressed a diverse range of topics that demonstrated the diverse character of industrialized construction practices. It was observed that the majority of the student projects adopted a near-site design scenario with hybrid design considerations. A situation that prompted class discussions regarding the importance of decision making in the design process and architectural solutions.

Although the majority of aspects in the design phase were adopted in the projects, the Digital Twin concept was more difficult to integrate due to the lack of foundational knowledge in modeling and simulation. Also, designing for connections and designing for modularization, were challenging aspects to achieve simultaneously. Another limitation is the post-design phase because the topics include a management vision. This suggests that additional lectures would have benefitted the studio, focusing on the characteristics of the post-design phase albeit at a theoretical level. To compensate for this aspect, complementary lectures related to the challenges of current global issues, such as climate change and health were given to the students. Thus, the final deliveries demonstrate a strong sense of social and ecological responsibility.

There is an opportunity to expand the potential of IC practices by thinking beyond the design methodology. Findings suggest modularity as a social connector, which in turn, serves as a component towards a more cohesive built environment. This study evidences the challenges of encompassing the post-design aspects into academic projects designed by students studying architecture. The present evaluation of the projects do not consider any post occupancy evaluation analysis. Instead, it considers a visualization of the assembly or delivery methods on-site only.

RECOMMENDATIONS FOR DESIGN PEDAGOGY

In this case study, students familiarize themselves with two Industrialized Construction concepts: Design for Manufacturing and Assembly and the Digital Twin. The evaluation of the design research pedagogy shows that it supports diversity of design explorations based on student interests. However, the analysis also points to the need for strengthening the technical skills of the students, before presenting them with the challenge of designing and modeling. The integration of IC concepts into a design studio was conducted in a senior design studio, with students in the Master of Architecture. More support is needed to prepare architecture students for Industrialized Construction practices.

Integrating IC in the Architecture studio sequence

Although the outcomes of this case-study show that the design studio remains central in design education as the environment where knowledge is integrated and synthesized, the integration of other perspectives would have enhanced the design research approach. For example the integration of Industrial design and Engineering design expertise would have benefitted modularization strategies explored in the course. These types of expertise can be integrated in a variety of ways, through lectures, external reviewers and guests, or through co-teaching with other disciplines. We believe that a multidisciplinary design studio focused on IC practices is critically important in the architecture studio sequence. Architecture programs can generate a variety of interdisciplinary IC studios, based on the areas of focus and strength of each program.

Integration IC in the Building Technology sequence

IC is a fundamental transformation of how buildings are designed and produced. Therefore, a new curricular paradigm is needed to integrate computational design literacy and understanding of building systems. In general, students should be given more support in understanding and utilizing Building Information Modeling (BIM) and building simulation. This can be done by reconsidering the computer aided design as separate from the building technology in architectural design curricula. Once is indeed a tool for the other. For example students learning about the use of 3D printing in architecture, should also be encouraged to consider the carbon footprint implications as well as energy use. These issues could be examined with a Digital Twin. We believe that an integrated approach to building technology is fundamental to Architecture Design Education. The Building Technology sequence of means and methods could integrate labs where digital modeling tools could be utilized for assignments and focusing on modeling, analysis, and decision-making.

CONCLUSIONS

This case study presented shows that it is possible to adopt an industrialized construction methodology in the classroom. The methodology observed in this study can be applied to both in-person and digital courses.

By applying a design research pedagogy, students can make decisions about the focus of their work and develop critical thinking about the integration of new technologies to impact larger questions at the intersection of design, justice, and ecology. This approach to introducing IC concepts fostered diversity of projects in the classroom. It can evolve from a pre-brief to the final delivery of the class. It also serves as the integral evidence of the class by retrieving all the projects developed in the classroom.

The guidelines from AIA and RIBA provide a framework to guide the evaluation of learning outcomes. The results of the analysis suggest that a new version of this course could be extended into the post-design phase by evaluating impact on labor reduction, productivity improvements on-site, manufacture and site preparation, and post-occupancy evaluation. The architectural projects developed under an innovative approach are a step forward for preparing young architects to apply IC methods in the practical field.

ACKNOWLEDGEMENTS

Thanks to Logan Brammeier, Charley DeVries, Robbie Edberg-Oostdik, Shawn Khokher, Andrew Klenke, Victor Renteria, Rebecca Twombly, and Tyson Washington for their work, dedication, enthusiasm, and resilience.

APPENDIX

Figure 0. Comparison of modular approaches described by AIA and RIBA guidelines.

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Guideline	Pre-design		Design			Construction	Handover	In Use
RIBA	0	1	2	3	4	5	6	7
DfMA RIBA's Plan of Work 2020	Strategic Definition	Preparation and Briefing	Conceptual Design	Spatial Coordination	Technical Design	Manufacturing and Construction	Handover	Use
Stage Outcome	Client Requirements confirmed	Project Brief approved by the client	Architectural Concept approved by the client and aligned to the Project Brief	Architectural and engineering information Spatially Coordinated	All design information required to manufacture and construct the project completed	Manufacturing, construction and Commissioning completed	Building handed over, Aftercare initiated and Building Contract concluded	Building used, operated and maintained efficiently

Sub-guideline	Off-site and near site pre-manufacturing					Site based process improvement	
GOV.UK	1	2	3	4	5	6	7
Modern Methods of Construction (2019)	Category 1: Pre-manufacturing (3D primary structural systems)	Category 2: Pre-manufacturing (2D primary structural systems)	Category 3: Pre-manufacturing components (non-systemised primary structure)	Category 4: Additive manufactoring (structural and non-structural)	Category 5: Pre-manufacturing (Non structural assemblies and sub-assemblies)	Category 6: Traditional building product led site labour reduction/ productivity improvements	Category 7: Site process led site labour reduction / productivity / assurance improvements
Building components	Systemised approach based on volumetric construction.	Systemised approach using flat panel units used for basic floor, wall and roof structures of varying materials which are produced in a factory environment and assembled at the final workface to produce a final three-dimensional structure.	Use of pre-manufactured structural members made of framed or mass engineered timber, cold rolled or hot rooled steel or pre-cast concrete. Includes: load bearing beams, columns, walls, core structures and slabs that are not substantially in-situ workface constructed and are not part of the **systemised design.**	Site based or final workface based printing parts of buildings through various materials based on digital design and manufacturing techniques.	Non-structural walling systems, roofing finish cassettes or assemblies, non-load bearing minivoumetric units (kitchens, bathrooms, cupboards, risers, plant rooms, preformed: wiring looms, mechanical eng.)	Traditional single building products manufactured in large format, pre-cut configurations or with easy jointing features to reduce extent of site labour required to install.	Utilising innovative site based construction techniques that harness site process improvements falling outside the five main pre-manufacturing categories 1-5 or materials innovation in category 6.

Guideline	Pre-design			Design										Post-design	
AIA	1	2	3		4	5	6	7	8	9	10	11	12	13	14
Design for modular construction: an introduction for architects 2019-2020	Legality, financing, and insurance	Delivery model	Compliance		Coordination	Engage a modular manufacturer	BIM	Integrated process	Initial design considerations	Connections	Design for disassembly	Modularization	Design freeze	Manufacture and site preparation	Transport, staging, assembly
Stage Outcome	To establish which party is responsible for the modular components—and for the associated financial and insurance liability—at each point in the process, particularly during the transportation and delivery of modules to the job site.	The owner and project team develop a design in isolation from contractors until the bid process, by which time the design has advanced to the point where the team may be unwilling or unable to make changes to optimize for modular construction.	Project teams should coordinate with the construction manager early in the process to determine what the local permitting requirements will be. Modular buildings will need to meet all applicable codes in the city and state where it will be located, regardless of where it was manufactured; project teams should ensure these code requirements are communicated to all parties, included in specifications, and integrated into the project planning process from the outset of design.	The order of the design subphases is not strictly specified by AIA.	From pre-design to design.	Once a modular project is ready to proceed beyond schematic design, the modular manufacturer should be brought on to provide consultation and, potentially, design-assist services.	Building information management (BIM) tools like Revit can contribute significantly to a wellcoordinated design, manufacture, and assembly process. For example, BIM can be used to plan sequencing to ensure that construction tolerances are maintained, and the clash detection features of BIM tools can help avoid conflicts at mate lines.	When designing for modular construction, the project team should shift their perspective to thinking of the building as a system of connected components. This view can help open up a larger field of possibilities for how modularization might be implemented, leading to a more iterative and less linear design process. The concept of modularity should ideally be embedded in and inform all phases of a project, not just the construction phase.	1. The **geometric design** of the constituent modular components (and, ultimately, of the building as a whole) will also be affected by transportation-related constraints on the size and shape of modules. Further, the manner in which the building will be divided into modules will affect the design of interior layouts and floor plans. **2. Parametric design tools** can provide for a wider range of options in modular construction. The design team may experiment with these tools to create variations of the standard module to be used on a project while remaining within the parameters defined by what the manufacturing process can costeffectively achieve. 3. **Collaborating with the modular manufacturer to build prototypes**.	In order to ensure ease of assembly and potential for disassembly, the design team will need to carefully consider not only how modules will connect to each other, but also how the modules connect to site-built components, including the building foundation, structural elements, and, on larger projects, elevator and stair cores.	Modular projects may be designed to enable disassembly—whether it's to maximize sustainability or to meet a project requirement for future relocatability or repurposing. This generally entails a higher degree of simplicity and repetition at the component level as well as access to connections. In modular construction, design for disassembly also involves maximizing the proportion of components manufactured off-site. A building completed 90 percent off-site will generally consist of more distinctly modular components and be more easily disassembled than a building completed 50 percent off-site and 50 percent on site, which will likely consist of fewer modular components and thus require more demolition. For disassembly design features to be effective, they must be apparent to and understood by whatever parties in the future may be responsible for the building's deconstruction. The design team should produce documentation of how the building was put together and how it's meant to be taken apart.	Once the building design has been fully developed, the modular manufacturer will work with the design team to create a "modular key plan"—essentially a plan for how the building will be divided into constitutive modules.	It's important to establish a design freeze when using a modular construction approach because design changes late in the process can be costly. Unlike traditional construction processes— which are more sequential and make it relatively easy to make design changes—a lot of the work is done simultaneously in modular construction processes, leaving little time in the schedule for alterations.	A primary benefit of modular construction is that it allows for building components to be constructed at the same time that site work is being completed. Once manufacture and site operations commence, the project manager should maintain regular communication with the modular manufacturer and the construction manager to make sure that the parallel processes are closely coordinated and proceeding in step with each other, according to the schedule.	Delivery timetables should be carefully coordinated and adjusted according to the progress of the assembly process. Depending on the size of the project, the fabrication process may need to be expedited or scaled up to keep pace with the rapid speed at which the modules can be assembled.

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ADDITIONAL MATERIAL

1 The Studio 812 documentation is available in the following link: https://issuu.com/system812_dfma___digital_twin_-_pages