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A comparative case study from a modularity perspective

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Chapter 4: Project Delivery Methods to Digital Fabrication in Architecture: A Comparative Case Study from a Modularity Perspective

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Abstract

Digital Fabrication (DFAB) faces challenges in project delivery due to various barriers, such as its complex technical processes and unclear benefits. However, there is no specific research on project delivery methods for DFAB. This study conducts a comparative case study to understand the delivery of projects with varying degrees of DFAB implementation. Modularity theory is used as a lens to explore project delivery methods. This study tentatively proposes strategies for establishing potential project delivery methods for DFAB. The research identifies three key characteristics: 1) the adoption of modular products and processes, 2) the adoption of an integral type of project delivery method, and 3) the significant role of informal relationships in project delivery. The study finds that misalignment relationships at the product, process, and supply chain levels, namely the combination of modular products and processes with integral supply chains, have fostered flexibility and coordination in DFAB project delivery. Theoretically, this study discusses the symbiosis and interrelationship between modularity and integration within the context of project delivery. Practitioners can build on these strategies to establish project delivery methods.

Keywords: digital fabrication, project delivery method, integration, modularity, case study

4.1 Introduction

Integrating Digital Fabrication (DFAB) in the Architectural Engineering and Construction (AEC) industry is a complex design and construction process. DFAB refers to data-driven production, where the generated workflow and data enable numerically controlled manufacturing equipment to fabricate parts or products (Bock and Linner, 2015, Ng et al., 2021). Empirical investigations have revealed an increasing number of digital instruments, such as the processes of 3D printing and robotic manufacturing and assembly, which have significantly enriched the practice of DFAB (Agustí-Juan and Habert, 2017). The potential and capabilities of DFAB are transformative in nature, particularly in how structures are conceived and materialised (Pawar et al., 2017). Nevertheless, the adoption rate of DFAB within the AEC industry remains low (Ng et al., 2022, Ng et al., 2021). The application of DFAB in the AEC industry faces complex challenges, including technical expertise requirements, high implementation costs, regulatory constraints, and significant shifts in traditional design and construction paradigms (Tan et al., 2023).

A significant barrier to the implementation of DFAB is the project delivery methods. DFAB necessitates an elevated level of coordination to ensure that all parties involved can efficaciously collaborate throughout the project lifecycle (Ng et al., 2022). During the process of project delivery, seamlessly integrating various DFAB technologies and tools constitutes a significant challenge. Substantial integration can also consume a considerable amount of time and cost, leading to an extension in the implementation timeline of DFAB. Therefore, in addition to integration, modularity approaches are required as well (Graser et al., 2021). Furthermore, the AEC industry is characterised by stringent regulations and standards, whilst DFAB is a new field. Despite successful delivery instances for some unique cases, DFAB lacks project delivery method research for wider implementation and standardised adoption.

Advancements in digitally enabled project delivery are poised to augment the implementation efficiency of DFAB. A research gap resides in the relationship between project delivery methods and DFAB. DFAB comprises various techniques, such as 3D printing, robotics, and computer numerical control cutting. The extent of DFAB implementation varies across different projects, which impacts the considerations for adopting project delivery methods. For instance, certain projects may only incorporate DFAB for partial components, whilst others might embrace DFAB across the entire building. Presently, there is no standardised metric to gauge the degree of DFAB implementation, which also challenges understanding the relationship between DFAB and project delivery methods.

This study aims to explore the implementation of DFAB in architecture from the project delivery perspective through a comparative case study. The study initially delineates four levels of implementation of DFAB, four types of project delivery methods, and project delivery strategies from a modularity perspective in Section Two. Subsequently, Section Three introduces the research methods. Section Four describes the implementation of project delivery methods and DFAB technologies in two specific projects. Finally, the study discusses the advancements, insights, challenges, and future research directions in this field.

4.2 Project delivery methods to DFAB through a lens of modularity

4.2.1 Implementation of DFAB

There has been no research concerning the degree of DFAB implementation. Based on the four-level model of modular and offsite construction concepts proposed by Pan (2019), DFAB could also be categorised to facilitate understanding its implementation. The degree of DFAB implementation in a project can broadly be encapsulated in four levels (see Figure 1). The Full DFAB level involves an extensive application of DFAB technologies in most or all processes, representing a degree of implementation between 60% and 100%. Hybrid DFAB is a level where DFAB coexists with traditional manufacturing techniques, contributing to a 30% to 60% degree of implementation. Partial DFAB, on the other hand, indicates a project where a fraction of processes involve DFAB technologies. While less dominant, this 15% to 30% degree of implementation still influences the project's success. Finally, the Minimal DFAB is the stage with the lowest degree of implementation, where DFAB technologies are sparingly used, often in very limited steps, indicating a 0% to 15% degree of implementation. Each level signifies a different extent of DFAB implementation, offering a flexible approach depending on a project's specific characteristics and needs. The degree of DFAB implementation could be quantified through a formula encompassing three key parameters: the proportion of DFAB data, the proportion of DFAB equipment usage, and the proportion of workflow steps involving DFAB. The degree can be computed as the weighted average of these parameters.

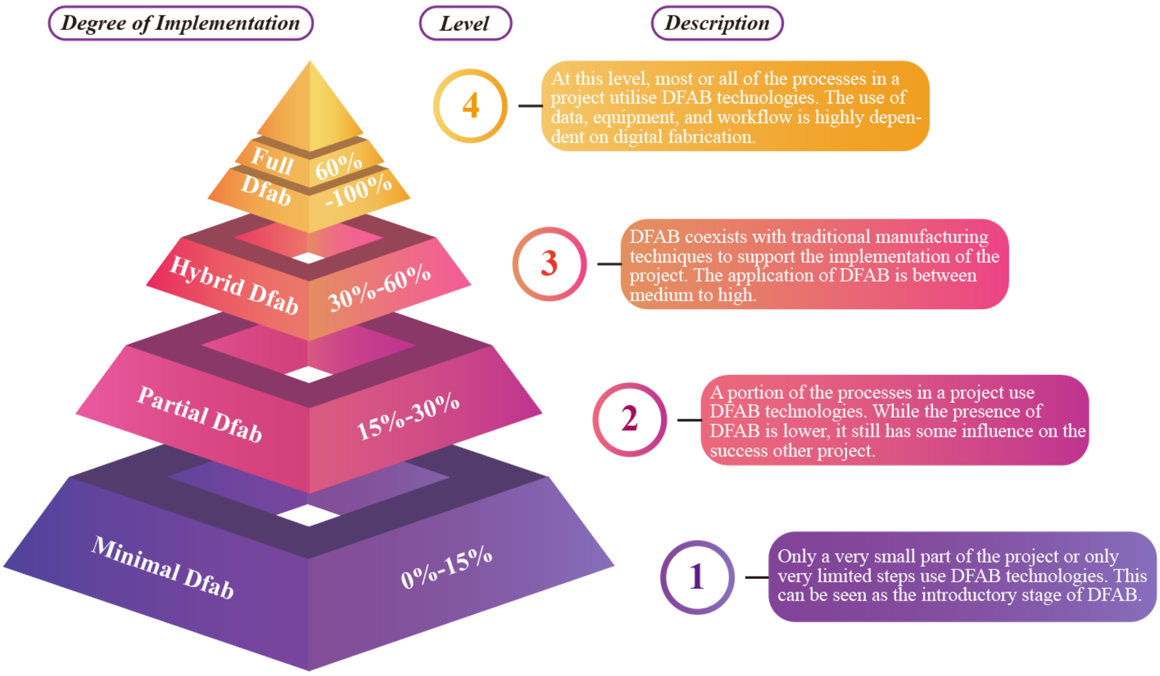


Figure 1. Implementation degree of DFAB in architecture

4.2.2 Supply chain modularity and project delivery methods

A project delivery method is a system employed by project owners or managers to systematically arrange and fund a project or facility's design, construction, operations, and maintenance aspects (Al Khalil, 2002). This involves forming contractual agreements with one or more parties involved in the project. There are several commonly used methods for project delivery. These include Design-Bid-Build (D-B-B), Design-Build (D-B), construction manager at risk, construction management multi-prime, public-private partnership, and Integrated Project Delivery (IPD). Voordijk et al. (2006) established the connection between project delivery methods and supply chain modularity. Modularity refers to a hierarchical system structure consisting of smaller sub-systems that can be designed independently but operate as a holistic system (Baldwin et al., 2000, Ulrich, 1995). Modularity is a relative system attribute (Baldwin et al., 2000). Every system is somewhat modular (Campagnolo and Camuffo, 2010), or integration. Modularity research in the supply chain is an emerging area (Salvador et al., 2002, Voordijk et al., 2006), and is spreading in construction (Doran and Giannakis, 2011, Voordijk et al., 2006). The trend to modularise the supply chains facilitates the transformation and reorganisation of value creation within supply chains (Doran and Roome, 2003, Collins et al., 1997). Supply chain modularity refers to whether certain supply functions or tasks are conducted by a single supplier or not and whether they can be explicitly distinguished from others (Wolters, 2002), thus aiming to mitigate the complexity within supply chain coordination. Supply chain modularity focuses on the division of labour within a supply chain network for specific supply chain functions and tasks and how companies interact, which is for a relatively flexible and interchangeable relationship among suppliers, customers, and partners (Fine et al., 2005). By analogy with modular products and processes, a modular supply chain responds to the changing demands on functionality and performance of different supply chain variants by cultivating alternative capabilities to deal with different versions of functional components (Voordijk et al., 2006).

In the AEC industry, Voordijk et al. (2006) claim supply chain modularity is assessed based on the separation or integration of design and execution responsibilities within organisational models. When design and execution are separated, there is usually higher modularity; for example, in the traditional model, components and responsibilities are distinctly allocated through multiple contracts. However, in integrated models such as the D-B approach, one organisation handles both design and construction, leading to less modularity. The least modular is the brochure plan model, where a single dominant entity controls all supply chain stages, including assembly and manufacturing (Voordijk et al., 2006). As shown in Figure 2, Fine et al. (2005) predict that a modular product tends to be designed by a modular process and modular supply chain. Voordijk et al. (2006) further test and describe this proposition in construction by adopting the variations of project delivery methods as different modularity strategies. However, Tee et al., (2019) assert that modular designs may mitigate coordination problems by decreasing the interdependencies between modules. These designs could also impede collaboration due to the increased focus on specialisation within the modules. This elucidates that modularity and integration, typically seen as contradictory, can also function in a complementary manner. Hence, there is a potential for better flexibility and coordination through misalignment, as opposed to the sole presence of the alignment relationship, as suggested by Fine et al. (2005) and Voordijk et al. (2006).

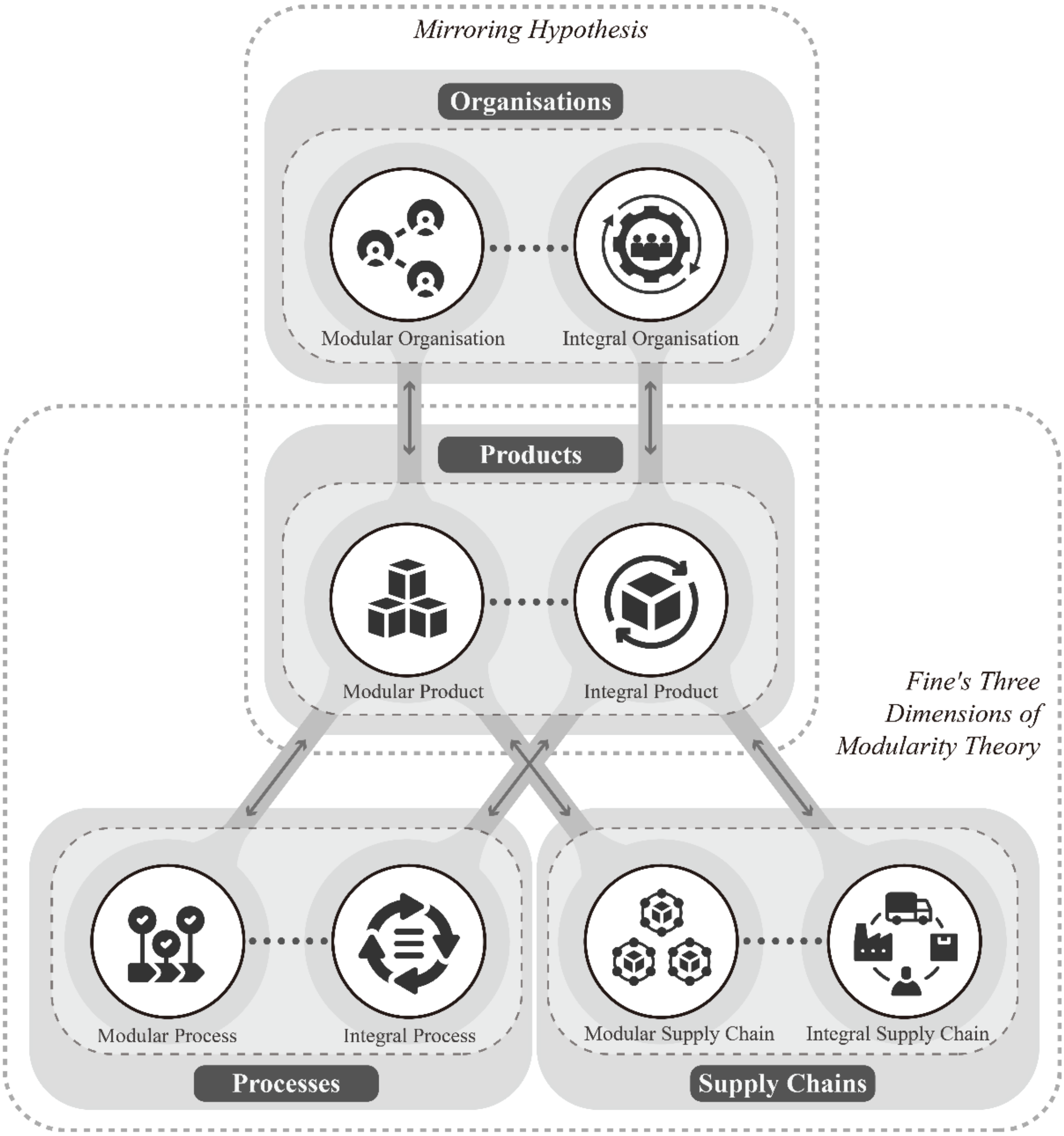


Figure 2. Relationships between multiple dimensions of modularity (Tan et al., 2024)

4.2.3 Four types of project delivery methods categorised based on modularity lens

Based on the modularity lens, project delivery methods could be divided into four types through two dimensions: vertical integration, vertical modularity, horizontal integration, and horizontal modularity (see Table 1). The table categorises project delivery methods through vertical and horizontal dimensions of modularity and integration. Vertical integration, exemplified by the D-B model, features a hierarchical structure with a single entity managing multiple stages, ensuring streamlined communication. Vertical modularity, as seen in the D-B-B method, involves dividing the project into stages managed by different entities within a hierarchical structure, providing flexibility but possibly disjointed communication. Horizontal integration, demonstrated by IPD, emphasises collaboration across different teams at the same level within the organisation, fostering resource sharing and collaborative decision-making. Lastly, horizontal modularity, represented by the construction management procurement route, involves segmenting the project into independent modules managed by different teams at the same organisational level, promoting flexibility and specialisation but potentially facing coordination challenges.

Table 1. Four types of project delivery methods categorised based on the modularity theory

Category	Definition	Advantages	Disadvantages	Examples
Vertical Integration	A project delivery method where multiple stages or components (e.g., design, procurement, construction) are managed by a single entity or closely aligned team. This typically involves a centralised decision-making structure and a high level of control.	Increased efficiency, reduced communication delays, and clear lines of responsibility and decision-making.	Potential for less flexibility, and can be less adaptable to changes.	Engineering, Procurement, and Construction (EPC), Design-Build.
Vertical Modularity	A project delivery method where different stages or components of a project are managed within their own vertical hierarchies but are relatively separate across the project. This allows for greater specialisation and independence within different stages of a project.	Allows for specialisation, clear phase responsibilities.	This can result in communication barriers, coordination challenges between phases.	Design-Bid-Build
Horizontal Integration	A project delivery method where various stages and components of a project collaborate and share information and resources on the same level. This typically involves cross-functional teams and a highly collaborative work environment.	Enhanced collaboration, greater flexibility and adaptability, conducive to innovation.	Potentially more complex decision-making, may require more time for consensus building.	Integrated Project Delivery (IPD)

Horizontal Modularity	A project delivery method where different stages or components of a project operate as relatively independent modules on the same horizontal level. This allows each module to have a degree of autonomy while coordinating and collaborating as needed.	Flexibility, modular collaboration as needed.	Potential for inconsistencies across modules, coordination can still be a challenge.	Construction Management Multi-Prime

In project delivery methods, applying modularity theory helps in understanding how to organise and optimise resources, responsibilities, and communication in project management processes. The distinction between vertical and horizontal further describes how modularity and integration occur across different levels within an organisation (see Figure 3). Vertical integration and modularity primarily deal with hierarchical structures, where responsibilities are either consolidated under one entity (integration) or divided among different entities in a tiered manner (modularity). On the other hand, horizontal integration and modularity focus on collaboration and division of tasks, respectively, across teams or units at the same organisational level, emphasising peer-level coordination and resource sharing. In summary, incorporating the ideas of modularity theory provides more structural insights and flexibility for the delivery of construction and engineering projects.

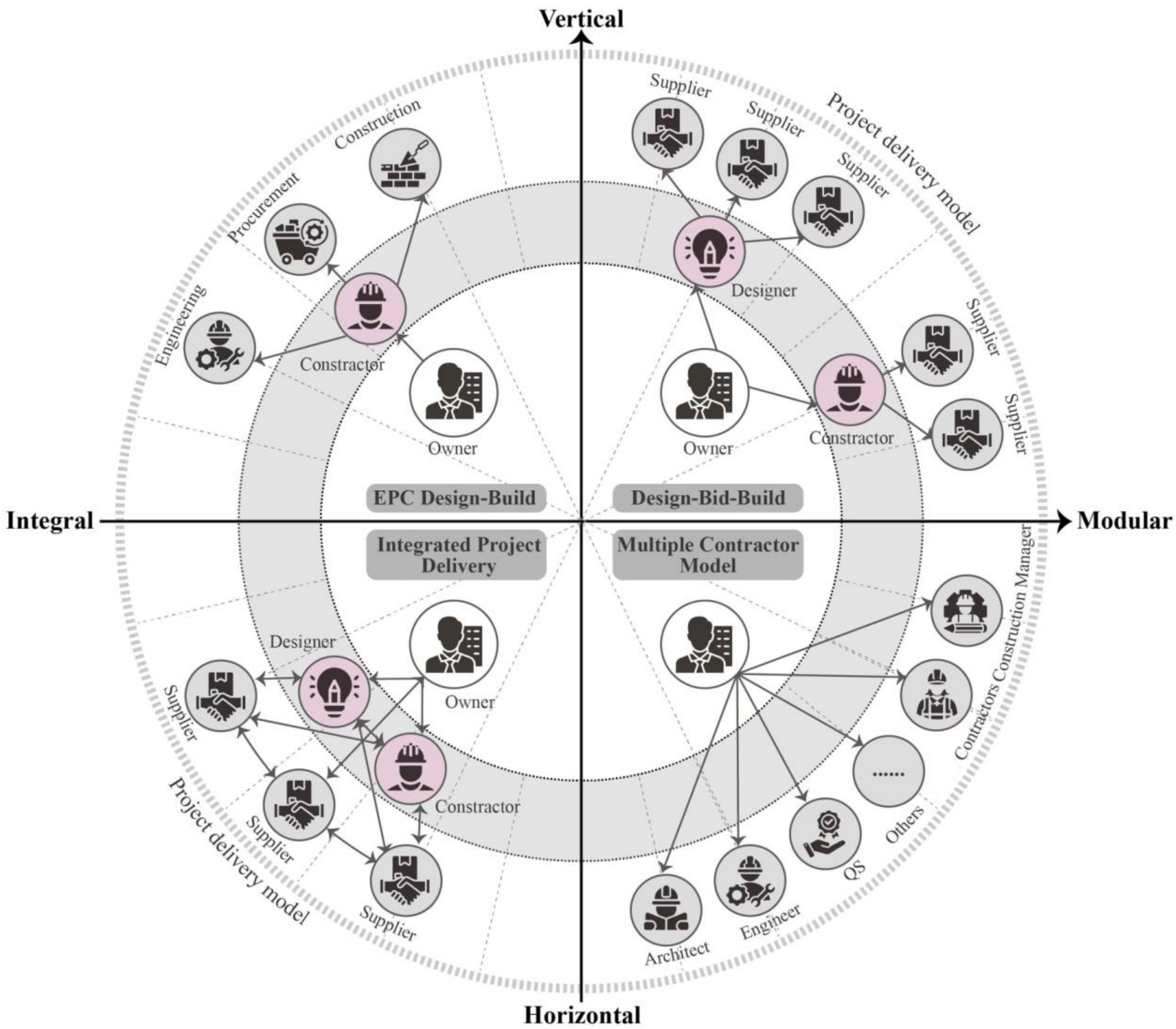


Figure 3. Integration-Modularity in project delivery methods

4.3 Methodology

A comparative and exploratory case study was conducted to analyse and compare the relationships between DFAB implementation and project delivery methods. The case study is a well-established approach to reveal and explore emerging context-based phenomena (Yin, 2009). DFAB is new to the wide industry implementation. Thus, an exploratory study would be beneficial to understanding its project delivery. Some of the authors were personally involved in the design and construction processes of these two DFAB projects. This study adopted an analysis strategy to compare the levels of DFAB implementation and integration-modularity in project delivery methods. The framing and categorisation methods for these two comparative units have been clarified in the literature review sections. There are four types of DFAB implementation levels, including full, hybrid, partial, and minimal DFAB. Four types of project delivery methods through the lens of modularity include vertical integration, vertical modularity, horizontal integration, and horizontal modularity. The relationships between multiple dimensions of modularity (see Figure 2) are used as the overarching lens to see the relationships.

The case selection strategy aims to identify cases with different DFAB implementation levels and investigate if and how their implementation levels impact the project delivery method selections. Second, more importantly, to investigate if and how the project delivery methods have impacts on the DFAB implementation. A significant exploration is to see if Fine's three dimensions of modularity theory can be applied to analyse and explain the relationship between DFAB implementation levels and project delivery methods. For example, to see if there is an integral-modular alignment relationship across product, process, and supply chain. This study collected interview, observation, and archival data from two cases and conducted an interpretivism-based analysis of the case data.

This study identifies two cases. The DFAB House (i.e. Case A, see Figure 4), erected from 2016 to 2018, serves as a forward-looking residential model in Switzerland, demonstrating state-of-the-art DFAB methods like 3D printing and robotics. This initiative is a joint endeavour between the Swiss National Centre of Competence in Research (NCCR) DFAB, architects, construction firms, and scientists showcased on the NEST building of Empa and Eawag. This project has indeed elevated the benchmark for environmentally friendly and digitally fabricated architecture. Another case B is the Chinese Tujia Pan-Museum (See Figure 5). Case B is a museum construction project with a 40 000 m^2 gross floor area for the Tujia minority in Enshi, Hubei province, China. The design was from December 2017 to December 2018, and the construction was from February 2019 to July 2021. The Chinese Tujia Pan-Museum is an innovative approach to poverty reduction and cultural promotion among the isolated Tujia people. Honouring traditional architecture yet adopting a modern design, the building utilises sustainable, prefabricated timber, reducing costs, environmental impact, and potential indoor pollution.

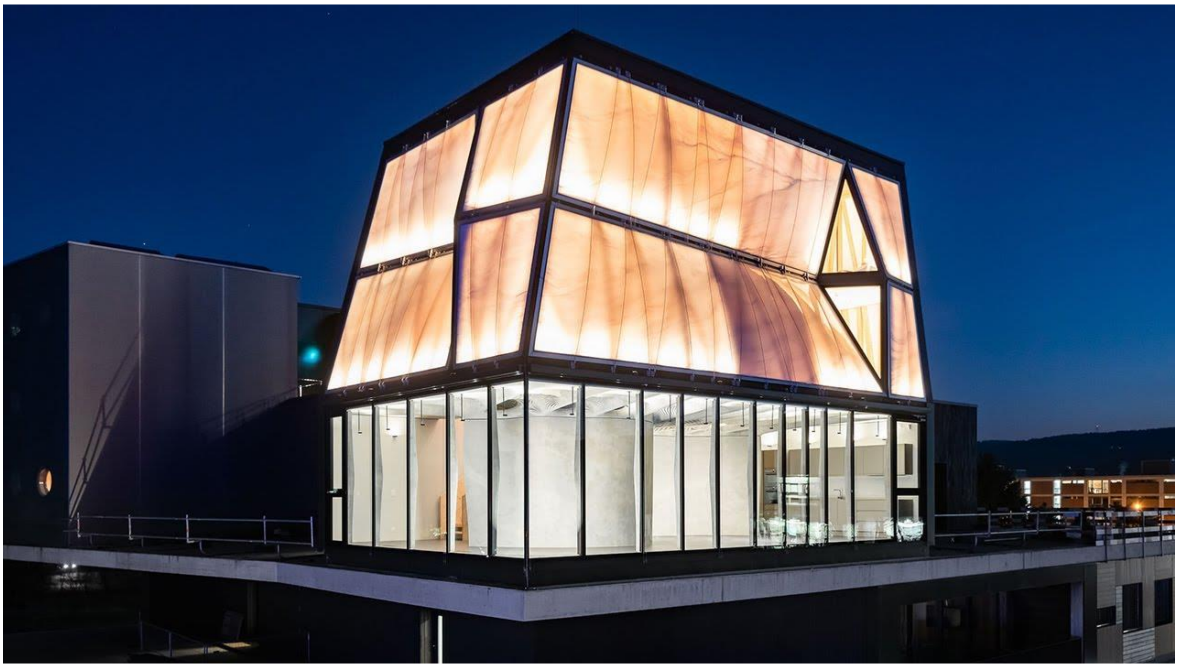


Figure 4. Case A: DFAB House (photo source: NCCR dfab)

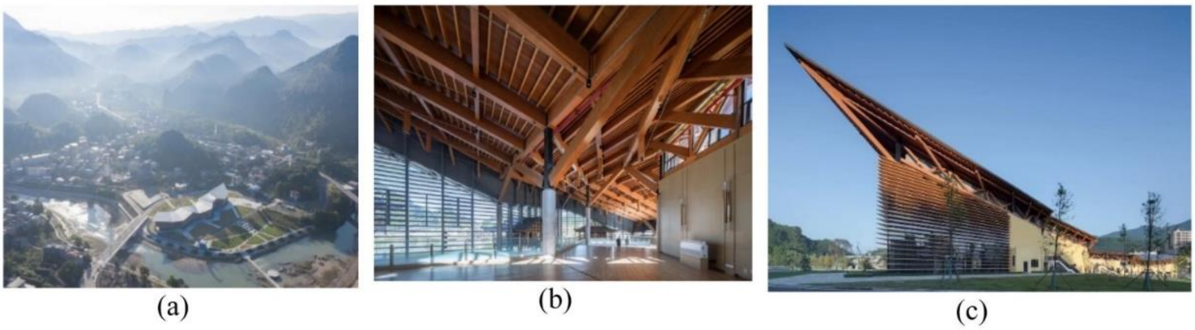


Figure 5. Case B: Tujia Pan-Museum (photo source: the author)

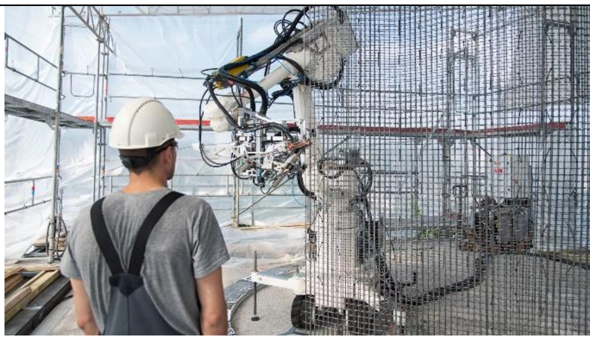
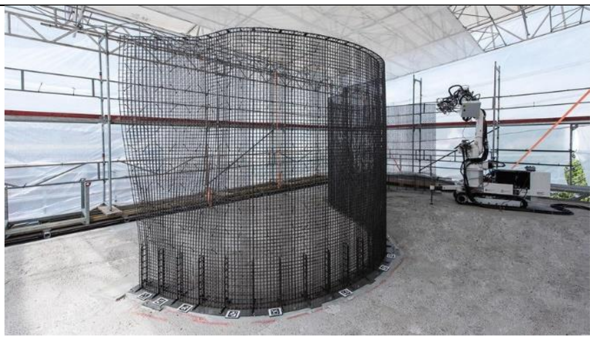
4.4 Case Studies

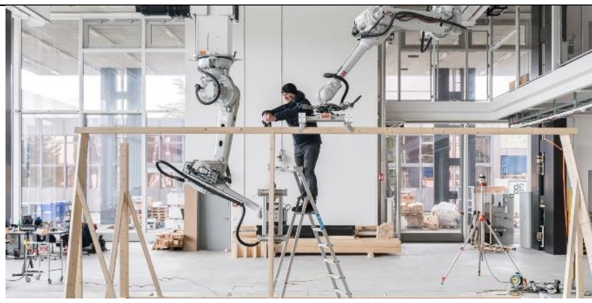
4.4.1 Case A: DFAB House

4.4.1.1 DFAB Implementation to Case A

The DFAB House (see Figure 4) integrates six novel digital building processes (see Table 2), including the In situ Fabricator, an autonomous construction robot, and the Mesh Mould, a robotic process for steel-reinforced concrete structures. The Smart Slab, a 3D-printed formwork for integrated ceiling slabs, and Spatial Timber Assemblies, a robotically fabricated timber structure, were also utilised. In the DFAB House project, the implementation of all these technologies is optimised and controlled through digital models and algorithms to achieve maximum efficiency and precision. The project demonstrates the potential of DFAB techniques in architectural design and production, capable of transforming how buildings are produced and how we understand architectural form and function. Regarding the implementation levels, the DFAB House can be regarded as a Full DFAB.

Table 2. DFAB techniques in DFAB house (photo source: NCCR dfab)

Technology	**Description**	**Benefits**	**Photos**
In situ Fabricator	A versatile autonomous on-site construction robot.	Allows for increased efficiency and precision in construction. Can operate independently, reducing the need for human labour in potentially dangerous environments.	
Mesh Mould	A formwork-free, robotic process for steel-reinforced concrete structures.	Eliminates the need for formwork, reducing material waste and labour costs. The process can create complex and bespoke shapes with reinforced concrete.	
Smart Dynamic Casting	An automated concrete slip-forming process.	This technique allows for the rapid construction of vertical concrete structures, saving time and reducing labour requirements. It also allows for the creation of	

		unique and complex forms.	
Smart Slab	Integrated ceiling slabs fabricated with 3D-printed formwork.	The 3D printing process allows for the creation of complex and bespoke shapes, which can be optimised for material efficiency and performance.	
Spatial Timber Assemblies	A robotically fabricated timber structure.	The use of robotics allows for precise assembly of timber structures, reducing waste and increasing efficiency. The process can accommodate complex and unique designs.	
Lightweight Translucent Facade	A membrane skin filled with translucent thermal insulation.	This facade technology provides insulation while allowing for natural light penetration, enhancing energy efficiency. It also offers a unique aesthetic due to its translucency.	

4.1.2 Project delivery to case A

The DFAB House project, an experimental, non-commercial initiative, was designed to showcase innovative research outcomes and required a significant transformation of conventional project delivery and roles. The project's unique approach combined D-B and IPD to synergise the efforts of planners, designers, and contractors, blurring the boundaries between planning and execution. It entailed adopting novel platforms like building information modelling and DFAB House plug-ins, prompting designers and engineers to assume roles like DFAB managers while also dealing with decreased personal involvement due to automation. Despite these novel adaptations, flexibility challenges arose within project relationships. Although formal contractual obligations existed between stakeholders, the exploratory nature of the DFAB house necessitated less formal, personal agreements and fostered a climate of interdisciplinary problem-solving. This necessitated more informal, organic collaboration mechanisms beyond formal established project delivery methods, often reflected in self-organised meetings among various experts such as roboticists, structural engineers, and material scientists. The project delivery also hinged on the integration of key actors early in the project timeline, especially during the conceptual stage, and the strategic co-location of the project team. This co-location fostered continuous interaction and collaboration, enhancing the collective body of knowledge. The industrial partners maintained a strong presence throughout the project stages, enabling direct involvement in planning, research, and industry decision-making processes. This proximity to production allowed stakeholders to move beyond remote judgements and gain a deeper comprehension of the project's needs, thus facilitating the exploration and realisation of DFAB's full potential.

The DFAB House project demonstrates a unique interplay between bottom-up self-organisation and top-down controls. This balance ensures that autonomous exploration aligns with the realities of project delivery. While research-led development is crucial, a more structured approach becomes necessary to prevent unending explorations from impeding project completion; as a contractor noted, "If you would have let them do this indefinitely, there still wouldn't be a finished building." Addressing this issue required modularity and integration in the project structure. Process modularity allowed each DFAB application to be independently and concurrently developed within its self-managed, highly integrated organisation module. Compared to software development by a project investigator, this approach decoupled operative project management from technology development and focused on integration, thus shielding researchers from the project's "managerial side". Such a strategy insulated the complex and uncertain aspects of DFAB development from interface interactions. However, coordinating interdependencies among multiple parallel DFAB developments posed challenges. A CEO highlighted the need for a seamless view of interfaces without sharp delineations of responsibility. Properly coordinated interfaces at module boundaries fostered the integration of different DFAB applications. A sense of collective responsibility was encouraged - "You are just a part of the project, you are not alone ... Everyone depends on the others." In this context, it's pertinent to discuss the role of "bridge function" actors. These individuals, possessing a broad array of skills and experience, were pivotal in managing information exchange across module interfaces. Their role was instrumental in the successful organisation of the project, illustrating the importance of roles that straddle both technical proficiency and cross-functional coordination in complex, exploratory projects like DFAB House.

4.4.2 Case B: Tujia Pan museum

4.4.2.1 DFAB implementation to Case B

In light of the considerable task volume inherent to timber processing, this endeavour employed robotic fabrication for the prefabricated timber rooftop assembly, as delineated in Figure 6. The technological groundwork for DFAB was provided by NURBS parametric modelling, specifically the Rhinoceros 3D software. The entity that manufactured the robotic appendages teamed up with a subcontractor to devise a timber structure processing plug-in, thereby enabling robotic fabrication, as detailed in Table 3. A virtual replication and generation of the physical robot arm's real-time operation were made possible within the 3D software environment, facilitating the simulation of all modular component fabrication and manufacturing procedures. The enhancement of the robotic arm's project-specific adaptability was a result of personalised software development and maintenance services. The integration of robotic fabrication with digital-enabled design has significantly bolstered design quality and production efficiency while concurrently mitigating labour requirements. Design information interchange at the corresponding phase is propelled by automated production implements.
However, from a holistic project scope, automation in construction constitutes merely a minor fraction. The ultimate architectural product is presently not factory-manufactured, indicating a substantial journey remains before complete automation dependency materialises for the final construction. The deployment of robotic arms is accompanied by numerous obstacles.

Equipment for processing has its limitations, encompassing component size, tool size and shape, and processing direction. These attributes invoke novel requisites for designers, necessitating intimate communication between designers and manufacturers to comprehend the characteristics of materials and processing and manufacturing capabilities, thereby achieving Design for Manufacture and Assembly (DfMA). Taking into account the DFAB conditions within this project, it can be perceived as a partial DFAB. Specifically, 15-30% of the construction is reliant on the DFAB process and associated technologies, such as the wooden roof structure. However, conventional construction techniques are still employed for aspects like the building's foundations, walls, and curtain walls, and they were subsequently amalgamated with the DFAB-produced wooden roof structure.

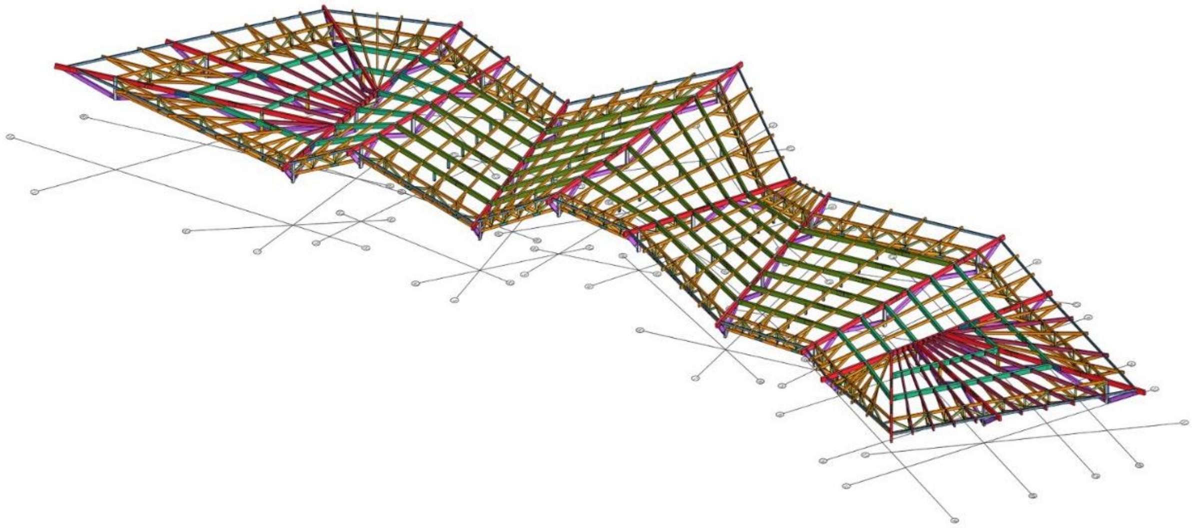


Figure 6. Prefabricated timber rooftop structure through DFAB

Table 3. DFAB techniques in Tujia Pan-Museum (photo source: the author)

Technology	Description	Benefits	Photos
Robotic Arm Cutting	A robotic arm equipped with cutting tools to perform precise and automated cutting of wood materials.	Contributes to increased efficiency, cost savings, and quality enhancement in manufacturing processes.	

4.4.2.2 Project delivery to Case B

In terms of project delivery methods, this project adopted the EPC model in the contract formation. However, in this project, the implementation of DFAB does not dictate the choice of project delivery method. Instead, the project delivery method was established first, followed by the decision on DFAB implementation. The substantial relationships of stakeholders within the project are not solely influenced by the contract-based project delivery method but, more importantly, depend on the informal relationships established through trust among the parties. These informal relationships are the primary factors affecting risk and responsibility allocation among all stakeholders in the project and essentially constitute the project delivery method rather than being fully determined by the contractual model. Although in theoretical EPC, the main contractor takes the lead, in this project, the chief architect, as the actual system integrator, played a leading role in promoting the implementation of DFAB and convinced the client to adopt DFAB. The conflict resolution and system integration issues in the implementation of DFAB are also aggregated to the chief architect. This informal project cooperation relationship, hidden under the formal EPC model, is a substantial factor that affects DFAB.

In this case, the integration and DfMA relied on the collaboration between the three parties' architects and the main contractor's project manager. The principal architect from the design firm took a major role in design changes, design optimisation, and DfMA process integration. The complexity of design activities is decomposed through the modular process. For example, engineers and manufacturers' design activities were 'hidden' and not directly involved in cross-organisation communication; they were led by the architects of their firms. The interface in the design process represents the rules of interaction and how different groups' design activities interact. For example, in this case, design firms prefer not to share all information or 3D models with other stakeholders because contracts have no such requirements. For example, the single-line model is usually a design task conducted by civil engineers. In this case, architects took the role of this design task and confirmed the section dimension size with civil engineers. Because civil engineers were not responsible for the appearance of forms and the aesthetics of the structural system, the architects allocated these tasks to themselves to keep design quality and make the OSC efficient. The change of design tasks was a reconfiguration of the design process. Relatively simpler information documents (i.e. single-line model) were exchanged as an interface for different design tasks between architects and civil engineers, representing the modularity in the design process.

4.4.3 Cross-case analysis

The comparative case study has revealed some similarities and differences in implementing DFAB. The extent of DFAB implementation affects the degree of change in the project organisation at the technical, procedural, and design levels. It can be seen in Case B that the extent of DFAB implementation is far less than in Case A. However, this does not mean that the implementation challenges faced by DFAB are reduced. In Case A, due to the deep implementation of DFAB, all project stakeholders have a greater consensus on the acceptance and understanding of DFAB. Additionally, as a non-commercial research-oriented demonstrator, all parties are more willing to embrace this change's interdisciplinary challenges, providing a foundation of trust and cooperation. On the other hand, in Case B, the implementation of DFAB is only executed in one part of the building (the roof), and communication and negotiation with multiple stakeholders involved in traditional construction are necessary. This situation presents not only interdisciplinary knowledge issues but also problems of trust and consensus on interests. Therefore, a lower degree of DFAB implementation does not necessarily mean lower implementation difficulties. Instead, at the level of project delivery, it may also face many challenges. These depend on the degree of correlation that the part implementing DFAB will have with other parts, i.e., the degree of independence or dependence of its DFAB component.

The shared insights distilled from the two case studies are as follows: 1) The adoption of modular products and processes; 2) The adoption of an integral type of project delivery method; and 3) The significant role of informal relationships. Whether it is the EPC, IPD, or DB, it can be seen that their inherent project delivery methods lean towards a more integral approach (see Figure 3). The real underlying stakeholder relationships within project delivery, which are established through informal relationships, also feature the commonality in both cases of assisting the design and workflow of the project to become more integrated, thereby resolving the challenges and problems in the engineering process. The type of informal relationship presents an inconsistency with the formal relationships among stakeholders established by contractual project delivery methods. However, this inconsistency does not necessarily have a purely negative effect. In the two cases selected for this study, these informal relationships have promoted the adoption and implementation of DFAB. Due to the establishment of formal contractual relationships, which are influenced and restricted by various policies, environmental factors, legal issues, and project backgrounds, informal relationships provide flexibility at the organisational and supply chain levels to implement DFAB. This relationship flexibility can help better implement relevant technologies and strategies in the early stages of DFAB introduction, compensating for the lack of an established and compatible DFAB project delivery method.

4.5 Discussion

4.5.1 Reflecting on the demarcation of modularity and integration in architecture

This comparative case study invites us to reconsider the prevailing definitions of modularity and integration within the field of architecture. Pan (2019) delineated modular construction as the apex of the offsite construction spectrum, wherein 60-90% of building components are fabricated offsite. According to this definition, the DFAB House described in Case A could be exemplified as a quintessential modular building. Nevertheless, a salient observation is the presence of multiple integrative measures in Case A, such as integrated project delivery solutions. DFAB is also regarded as a typical practice of integrative design, entailing a design-to-manufacture integration driven by design data. If integration and modularity represent the two extremities of a spectrum, how is this paradoxical phenomenon, the simultaneous presence of integration and modularity, realised? This question triggers researchers and practitioners to reconsider the definitions of these terms.

This study argues that modularity and integration can coexist due to inconsistencies among different system dimensions and hierarchical levels within an object. Therefore, the object under examination must be explicitly defined when discussing modularity and integration. For instance, in Figure 9, both A and B in the two illustrations are highly integrated internally due to their mutual dependencies and connections. The interface between the two modules is changed based on the reconfiguration of the two groups' design activities. With the change of boundaries (i.e. dashed boxes), the interface between two groups is changed from one connection to two connections, which is activated by the move of 'C'. The left side grouping way is relatively more modular than the right side. In addition, two modules formed by A and B are linked by Interface C, presenting A and B as highly independent submodules with modular characteristics from this perspective. This discrepancy results from scrutinising different levels of the modular-integrative spectrum. As illustrated in Figure 2, modularity and integration can exist in different dimensions (i.e., product, process, organisation, supply chain), and both Case A and Case B reflect a misalignment relationship between different dimensions of modularity. Specifically, both cases demonstrate modular products and processes, yet they simultaneously possess integral supply chain features.

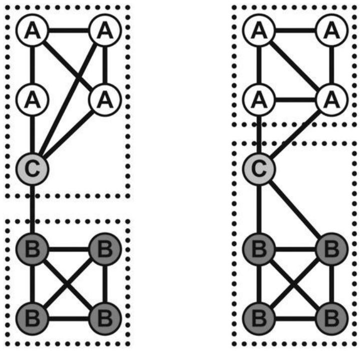


Figure 9. Reconfiguration of key design activities.

4.5.2 Reflecting on Fine's three dimensions of modularity theory

The conclusion diverges from Fine's three dimensions of modularity theory (Fine, 2010), but further builds on and develops Tee et al., (2019) arguments on the benefits of misalignment and complementarities between modularity and integration. In this comparative case study, the modular products of the two cases are formed by modular processes and integrated supply chains, representing a type of misalignment relationships amongst the product, process, and supply chain. "Misalignment relationships" in multi-dimensional modularity denote inconsistencies or unclear correspondence in the degree of modularity across different dimensions such as product, process, organisation, and supply chain. Theoretically, the degree of modularity in these different dimensions should be aligned, that is, modular products should be produced by modular processes, modular processes should be conducted within modular organisations, and modular organisations should be supported by modular supply chains. For instance, Voordijk et al. (2006) carried out research on the application of Fine's three dimensions of modularity theory in the construction industry and examined this alignment relationship. However, in practice, this alignment may not always be present, potentially leading to the so-called "misalignment".

Increasing the degree of process modularity and adopting modular processes may be attributable to the aim of reducing complexity during the design process and simultaneously enhancing the task flexibility of interdisciplinary teams, mitigating risks, and promoting system integration (see Figure 10). Within the context of DFAB, modular processes enhance project adaptability and efficiency. Independent module design, production, and assembly allow for swift adjustments amidst demand changes or technological innovations. Digital optimisation of a module can be immediately replicated across all relevant projects, significantly boosting efficiency. Quality control is also reinforced, as digitally controlled environments enable independent production and testing of modules, and any defective module can be rectified without disrupting the entire project.

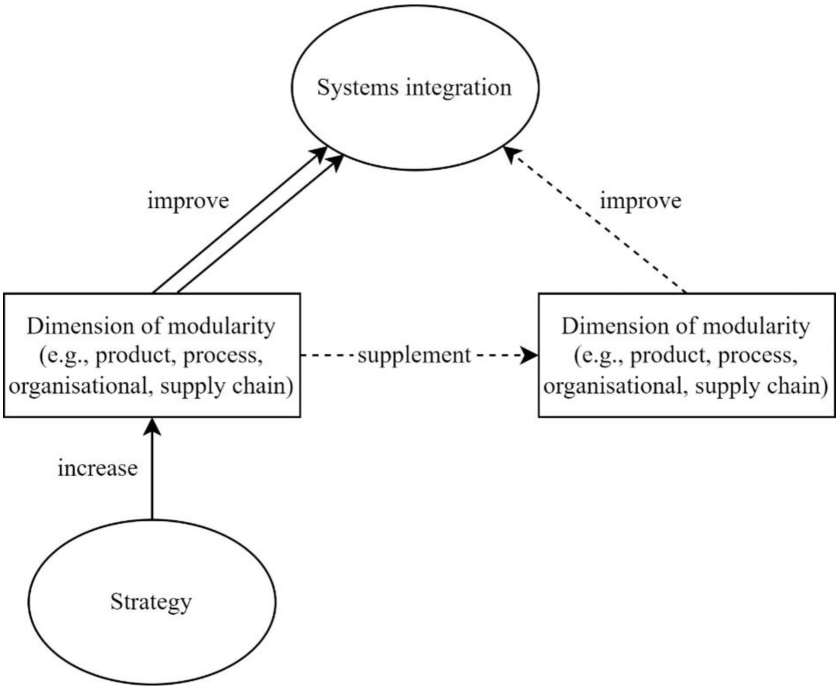


Figure 10. Modular complement relationship through the increase of modularity (i.e. addition complement)

Reducing the modularity scale of the supply chain and adopting an integrated supply chain could potentially be a strategy to address the complexity challenges inherent in implementing DFAB. This degree of misalignment may facilitate system integration by tackling the multifaceted issues associated with DFAB execution (see Figure 11). IPD and an integrated supply chain, used to enhance collaboration and quality control, can address the complexity challenges in DFAB. IPD encourages tighter collaboration among stakeholders, improving coordination, reducing errors, and raising project quality. An integrated supply chain allows for comprehensive quality control and traceability of each component. The full involvement of all parties across project stages often results in higher satisfaction with project outcomes.

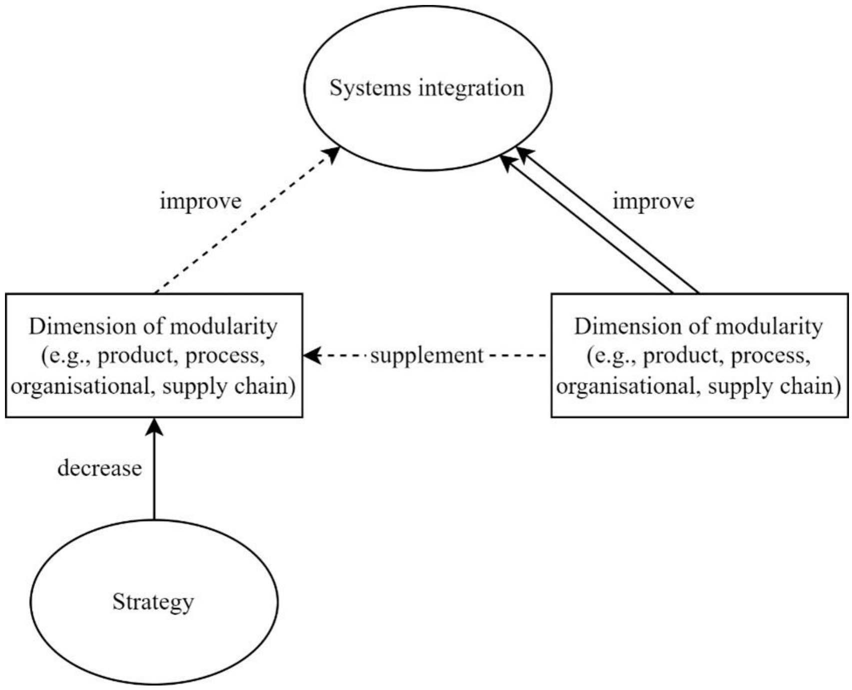


Figure 11. Modular complement relationship through the decrease of modularity (i.e. subtraction complement)

4.5.3 Reflecting on project delivery to DFAB

Understanding and managing modularity misalignment provides valuable insights for devising solutions suited for DFAB project delivery, especially under varying degrees of DFAB implementation. First, DFAB projects necessitate an integrated perspective on products, processes, organisations, and supply chains. This calls for comprehensive understanding and coordination to ensure effective collaboration. For instance, when using modular design and manufacturing processes, the supply chain and organisational structure must support this modularity. Higher DFAB implementation complexity may involve more automation and intricate data management.

Second, the potential unpredictability caused by misalignment demands flexible and adaptive project delivery solutions. This may imply utilising tools and methods that accommodate change, like agile development or planning for possible changes from the project's inception. Projects with lower DFAB implementation might require stronger flexibility and adaptability due to increased manual involvement and frequent alterations. Third, misalignment represents an opportunity for innovation and improvement in our project delivery solutions. This could include adopting new technologies or methods, improving processes or organisational structures, or finding better ways to coordinate our supply chains. In projects with lower DFAB implementation, innovation might depend more on human resources and knowledge, while technology and data might be key in higher implementation projects.

Although addressing misalignment might increase project complexity and difficulty, the long-term benefits are substantial. A highly modular and integrated project delivery solution enhances efficiency, quality, and satisfaction, boosting long-term project success. Different investments and strategies might be required for projects with varying implementation degrees for optimal results. Overall, understanding and managing the misalignment of modularity across various dimensions can enhance the design and implementation of DFAB project delivery solutions, improving project success rates. Strategies and methods must be tailored based on the degree of DFAB implementation to effectively tackle potential challenges and opportunities.

4.6 Conclusions

This study conducts a comparative analysis of two cases implementing DFAB at varying degrees (full and partial) to identify relevant project delivery strategic patterns. As the adoption of DFAB in the broader field of architecture and the exploration of associated project delivery methods remain emergent topics, this study attempts to fill a gap in the existing body of knowledge through its exploratory case study approach. A key finding is that the degree of DFAB implementation significantly influences the interrelationship between DFAB and project delivery solutions. The level of DFAB implementation doesn't necessarily correlate with the degree of difficulty or challenges faced; regardless of its intensity, DFAB implementation will impact project delivery solutions, but the manner of these impacts will vary. Projects with a high level of DFAB adoption necessitate sophisticated data management systems due to increased automation and interconnectivity, demanding a higher degree of collaboration. These projects face potential technological risks and require significant initial investments. However, they also present abundant opportunities for process optimisation and efficiency gains through data analytics and automation. Conversely, projects with a lower degree of DFAB adoption predominantly depend on human-centric coordination and traditional construction knowledge. While these projects may experience a greater likelihood of human error, they also leverage human creativity and experience for innovation. Initial investments for these projects tend to be smaller but may incur higher operational costs due to increased manual labour. Thus, project delivery solutions must consider these dynamics, tailoring strategies to suit the specific demands and conditions inherent in the degree of DFAB implementation.

This study invites a reconsideration of modularity and integration in architecture, using a comparative case study to show that these two concepts can coexist due to inconsistencies among different system dimensions and hierarchical levels. In the context of DFAB, modular processes increase adaptability and efficiency, while integrated supply chains tackle complexity challenges inherent in DFAB implementation. Notably, this study diverges from Fine’s three dimensions of modularity theory, revealing misalignment relationships among product, process, and supply chain. Understanding and managing this modularity misalignment is crucial for devising DFAB project delivery solutions. It necessitates an integrated perspective on products, processes, organisations, and supply chains. The unpredictability triggered by misalignment requires adaptive project delivery solutions and provides a platform for innovation. Despite the complexity of addressing misalignment, the potential for improved efficiency, quality, and satisfaction boosts long-term project success. In conclusion, managing modularity misalignment across various dimensions can optimise DFAB project delivery solutions, enhancing project success rates. Tailored strategies based on the DFAB implementation degree are required to effectively address potential challenges and opportunities. This comparative case study on DFAB project delivery has limitations. The research findings might be bound by the confines of theoretical models, such as the modularity theory, which have inherent limitations that affect outcomes. Future research could proceed in several directions:

- Comparing architectural projects and industries across different geographical contexts to better understand the role of DFAB in project delivery.
- Identifying measurable relationships and trends, complemented by longitudinal studies to uncover the long-term impacts of DFAB implementation.
- Examining the influence of evolving DFAB technologies, including AI, robotics and automation, on project delivery mechanisms.

4.7 Acknowledgement

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