Exploring Multi-Dimensional Modularity: Strategies to Reduce Complexity in Design Activities

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Abstract

Modularity is an approach to simplify systems and reduce complexity. However, existing research suggests that a mono-dimensional modularity strategy, focusing solely on one dimension, such as product, process, or organisation, might not fully achieve these goals in design activities. This research investigates how combining strategies from various dimensions of modularity can reduce the complexity of large-scale engineering design. The Huoshenshan Hospital, a 1,000-bed hospital designed and built in 10 days, provided an extreme case study of the first emergency hospital to address COVID-19. The research identified ten different aspects, termed 'proximities', which relate to how people perceive the four dimensions of modularity, specifically across organisation-process-product-supply chain dimensions. Additionally, it identified three types of reinforcement relationships aimed at diminishing complexity in design activities: modular alignment (i.e. synchronised alignment and asynchronous alignment), modular complementarity (i.e. subtraction complement and addition complement) and modular incentive relationships. This research highlights that these three types of reinforcement relationships between different dimensions of modularity can reduce complexity, allowing sub-systems to support the system in working as a whole.

Keywords: modularity, engineering design, design activities, construction, case study

1. Introduction

In the context of engineering and design, complexity often refers to the intricacy, interconnectedness, and multifaceted nature of components, systems, or processes. It can manifest in various ways and can be viewed from multiple dimensions (Braha, 2016). Individuals from various fields, companies, and locations collaborate. They interact with each other and with different objects. This creates a constantly changing network of activities and relationships (Wynn et al., 2005). Amidst numerous unrelated design tasks, processes, and decisions, unintended interactions can emerge, heightening the system's complexity. The exploration and reduction of complexity are of significant importance in comprehending and designing modern engineering systems (Simon, 1996). By delving into the intricacies of these systems, one can gain a deep understanding of their functionality and behaviour, leading to more efficient and effective design solutions.

Modularity is an approach to reduce complexity in design. It refers to the principle that a system is divided into separate components or modules, each responsible for a distinct function and working together as a whole. These modules can be created, replaced, or upgraded independently (Baldwin et al., 2000). In this research, multiple dimensions of modularity refer to the wide range of viewpoints and themes for defining modularity (Bask et al., 2010). Previous studies have explored mono-dimensional modularity strategies, such as product modularity (Gravina da Rocha et al., 2020; Zhou, 2023), process modularity (Bekdik et al., 2018), organisational modularity (Krinner et al., 2011), and supply chain modularity (Zhou et al., 2023). Nevertheless, in some design activities, employing mono-dimensional modularity strategies may not simplify systems or reduce complexity. For example, conflicts may arise between modular design strategies, such as standardisation and flexibility (Choi et al., 2022). Besides, by focusing on specialisation within modules, modularity might also hinder collaboration, especially cooperation (the willingness to collaborate) (Tee et al., 2019).

Previous studies suggest a potential relationship between two or three modular dimensions for reinforcement. The 'reinforcement relationship' refers to a synergy connection where systems of multiple dimensions (i.e. across product, process, organisation, and supply chain dimensions) strengthen each other, aiming for systems integration, which is the cohesive blending of these dimensions to function seamlessly as a unified whole. In other words, changes or adjustments in one dimension can positively affect another, ensuring harmonious functioning rather than isolation or conflict. Studies have explored the alignment relationships between product and process modularity (Da Rocha & Kemmer, 2018; Tan et al., 2022), product and organisational modularity (Hall et al., 2020; Tan et al., 2021; Tee et al., 2019), product and supply chain modularity (Hofman et al., 2009; Pero et al., 2015), product, process and organisational modularity (Jensen et al., 2014), and product, process and supply chain modularity (Doran & Giannakis, 2011; Voordijk et al., 2006). However, aligning multiple dimensions of modularity may not always lead to complexity reduction in design activities. For example, the 'mirroring hypothesis' (i.e. the alignment relationship between organisational and product modularity) is not a universal principle for design. The industry and firm studies showed that over two-thirds (70%) of the descriptive studies provide strong evidence of mirroring, 22% provide partial support, while 8% do not support the hypothesis (Colfer & Baldwin, 2016). For example, when the underlying technologies are rapidly changing and becoming more complex, breaking away from the logic of strict mirroring may lead to better technical performance and advantage (Colfer & Baldwin, 2016).

In architectural design, various modularity dimensions might operate independently. For example, a building project may deploy highly modular physical components but adhere to a design process that is less modular, thereby leaning towards a more integral process, which means a unified, cohesive design process. Alternatively, even when using a cast-in-situ type construction, some projects might still incorporate modular processes, implying that the process is less interconnected and cohesive. Integration practices, which entail combining different parts or systems into a harmonious whole, can complement the high level of modularity by stimulating collaboration (Tee et al., 2019). While modularity offers flexibility and adaptability, integration ensures synergy and unified operation. At present, research on multi-dimensional modularity relationships in engineering design is in its infancy, particularly in the context of large-scale complex engineering. Complex large-scale engineering projects require diverse design expertise and interdisciplinary collaboration to address complexity and challenges. As such, there exists a gap in research about how different dimensions of modularity can reduce complexity in design activities through their synergy.

This research explores how multi-dimensional modularity strategy can reduce complexity in large-scale engineering design, focusing on reinforcement relationships between the modularity dimensions. This research defines reinforcement relationship as the synergistic interplay between various modular strategies across multiple dimensions, all working together to reduce overall complexity. For example, when solving a puzzle, using one strategy to find corner pieces and another to match by colour can reinforce each other, simplifying a complex task, analogous to the 'reinforcement relationship' described. Both Hall et al.'s (2020) alignment relationship and Tee et al.'s (2019) complement relationship are reinforcement relationships between multiple dimensions of modularity to facilitate continuous collaboration and complexity reduction. The research question is: '*How does multi-dimensional modularity reduce complexity in engineering design?'* This main question branches into three sub-questions:

1) How is multi-dimensional modularity implemented?
2) How are the different dimensions of modularity related to each other?
3) How does the reinforcement relationship contribute to design complexity reduction?

This research examines the literature about the relationships between four modularity dimensions. Following this, the research outlines its single case study methodology. The results, presented in section 4, outline the measures of the four modularity dimensions in the case of Huoshenshan Hospital. In the subsequent section, the discussion analyses three relationship patterns between these four dimensions: modular alignment, modular complementarity, and modular incentive relationships. Finally, section 6 provides a conclusion summarising the findings of the study.

2. Relationships between the four dimensions of modularity

2.1 Defining modularity

The origins of modularity theory can be traced back to earlier theoretical concepts (Frandsen, 2017). For example, Simon (1962) proposes the concept of 'near decomposability', implicating systems can be decomposed into component sub-systems for complexity reduction. After that, Starr (1965) pioneers the concept development of 'modular production' to describe the capacity of design for manufacture in parts that can be assembled in multiple approaches. Furthermore, Weick (1976) introduced a concept termed ‘loose coupling’, which refers to systems with responsive elements that maintain physical or logical separateness, highlighting their advantage in localised adaptation. These close theoretical concepts provided the basis for the development and evolution of modularity (Frandsen, 2017). Terminologies such as ‘module’, ‘modular’, ‘modularity’, and ‘modularisation’ are often used interchangeably across various academic papers spanning different subjects. Nuances of modularity exist and vary somewhat based on contextual background, such examples ranging from several fields of science (i.e. biology, ecology, cognitive science), technology (i.e. modular programming, software design, self-reconfiguring modular robotic), industry (i.e. construction, industrial design, manufacturing, organisational design), and culture (i.e. new media, modular art).

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). Each industry has its own specific definition. In engineering design, modularity refers to products, processes, and resources that fulfil various functions by combining distinct building blocks (Bonvoisin et al., 2016; Kusiak, 2002). In technology and organisation, modularity refers to breaking up a complex system into discrete pieces upon a standardised architecture for their interactive communication only through standardised interfaces (Langlois, 2002). In the construction industry, modularity refers to a design approach that uses prefabricated standardised components or modules that can be easily assembled, disassembled, and reassembled in various configurations (Kluck & Choi, 2023; Ulrich, 1994). Recently, several studies have systematically reviewed the definition of modularity (Campagnolo & Camuffo, 2010; Pandremenos et al., 2009; Salvador, 2007; Sonego et al., 2018). A consensus among these studies is the emphasis on both interdependence within modules and independence across them, leveraging these features to address complexity by obscuring intricate parts behind abstractions and interfaces (Baldwin et al., 2000). In addition to interdependence and independence, Baldwin et al. (2000) captured the essence of modularity from three ideas: (1) abstraction, (2) information hiding, and (3) interface.

Four major dimensions of modularity have been identified: product, process, supply chain, and organisational modularity (Bask et al., 2010). Corresponding to the concept of ‘modularity-in-design’, product modularity entails a product design strategy using standardised and interchangeable components to configure various products (Gershenson et al., 2003; Schilling, 2000). By ‘design’ here, it means the conceptualisation and detailing of a product's components and their interactions. This is where decisions about the product's functionality, aesthetics, and features are determined. Process modularity, corresponding to 'modularity-in-production', mainly used for planning purposes, describes the degree to which a process can be decomposed into modules for parallel execution (Parraguez et al., 2019). 'Planning' in this context refers to the coordination and sequencing of tasks in the production pipeline. This approach allows for easier scaling, modification, and customisation of the production process without disrupting the entire system. 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. And organisational modularity is a loosely coupled network of autonomously operating self-contained units, having a low level of interaction but a high level of awareness among each other through standardised interfaces, which can be flexibly recombined into a variety of organisational configurations (Soyer et al., 2019).

2.2 Relationships between multiple dimensions of modularity

Design activities based on mono-dimensional modularity strategies might pose communication barriers in interdisciplinary teamwork, thereby hindering design performance. For example, Da Rocha and Koskela (2020) analyse the underdevelopment of product modularity in the construction industry. Pan et al. (2008) indicate that there is a misalignment between conventional procurement methods and the awareness levels concerning the incorporation of product modularity in early designs. Various causes from diverse dimensions, including organisational and technical dimensions, adversely affect the implementation of modularisation (Pan et al., 2023). Therefore, it's crucial for modularity to account for the coordination across multiple dimensions (Shafiee et al., 2020).

A growing body of research emphasises the utilisation of multi-dimensional modularity in design activities. Previous studies have explored various alignment relationship strategies between multiple dimensions of modularity, as shown in Figure 1. Da Rocha and Kemmer (2018) examine the alignment relationship between product modularity and process modularity, the positive impacts of alignment on architectural design, and the negative impacts of misalignment between product modularity and process modularity; Hall et al. (2020) explore ‘mirroring-breaking’ strategies to improve systems innovation by further understanding the alignment relationship between product modularity and organisational modularity; Tan et al. (2021) investigate the design for manufacture and assembly through the alignment of product and organisational modularity. On the other hand, some studies are now exploring the misalignment relationship. Tee et al. (2019) identify a complementary relationship (i.e. a type of misalignment) between modular design and integration practices, demonstrating that aligning multi-dimensional modularity is not always the best practice. However, a significant gap remains in the literature regarding a holistic understanding of the relationships between multi-dimensional modularity, as well as the inherent mechanisms that govern these relationships.

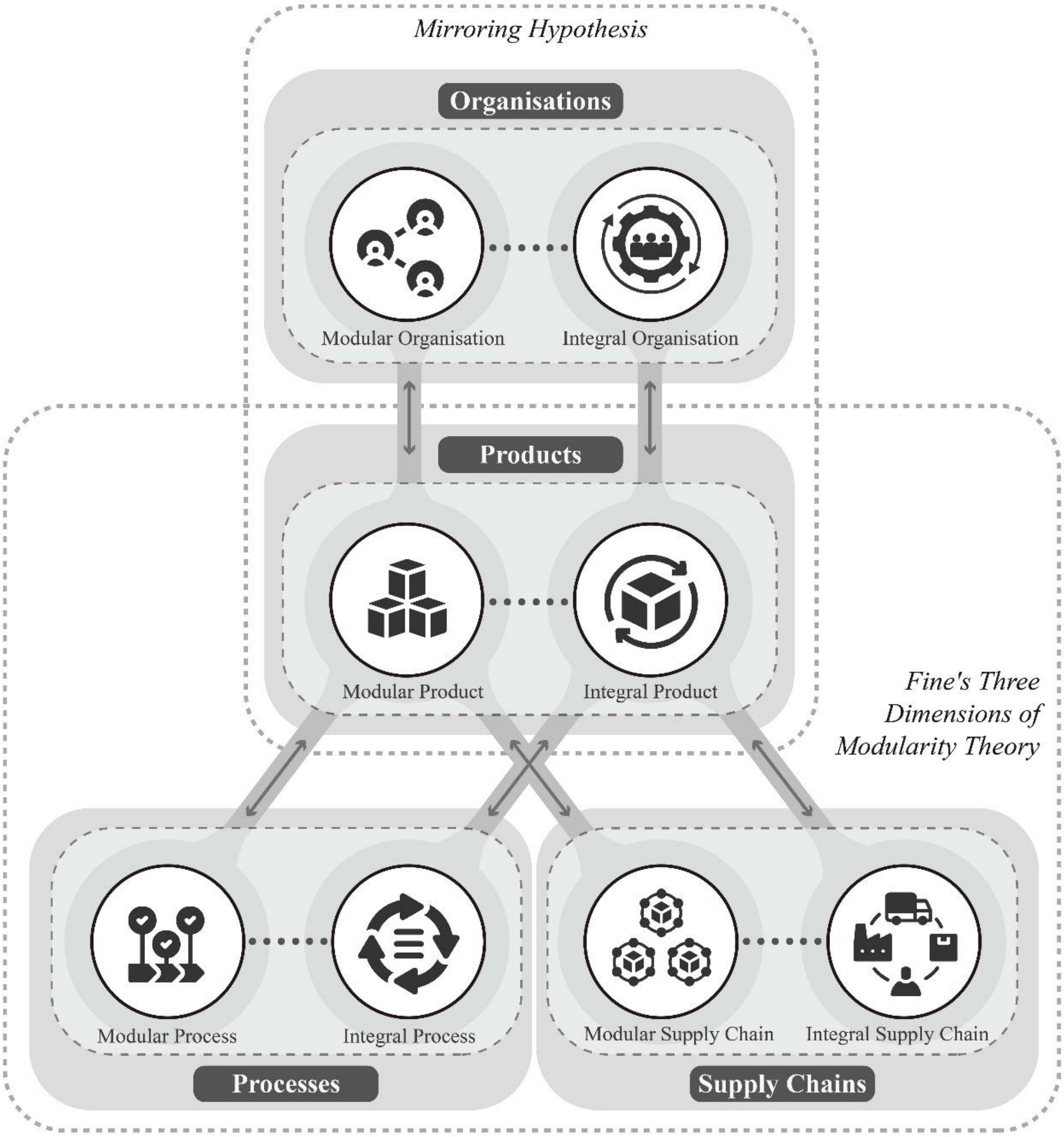

Fig. 1. Alignment between multi-dimensionality of modularity

Research into these multi-dimensional modularity relationships in engineering design, particularly in the context of large-scale complex engineering, is in its infancy. Pan et al. (2019) also stress the significance of employing a multi-dimensional perspective to foster modularity. They propose five visions for the multi-level framework, but further empirical evidence is needed to support and build on these recommendations. Therefore, this research addresses the research gap related to the lack of a comprehensive reinforcement strategy. By delving into and addressing these reinforcement relationships, this research seeks to enhance our understanding of how to reduce complexity in design activities.

3. Methodology

3.1 Single case study paradigm

This research sampling seeks to attain theoretical generalisability using a critical, extreme and revelatory case (Yin, 2017). This rationale supports the adoption of the single case study paradigm. Firstly, a single case was selected in this research to test the modularity theory. The propositions of modularity theory can be evaluated through a single case to determine its accuracy or if alternative explanations might hold more relevance. Secondly, the choice of a single case can be justified by its extreme or unique characteristics, which deviate from theoretical norms or common occurrences, thus offering insights about standard processes. Thirdly, exposing previously inaccessible phenomena and highlighting their revelatory nature can further justify the use of a single case study in theory building (Yin, 2017). Finally, addressing criticisms about generalisation, a single case study aims not to represent the world but to depict the specific case in focus (Stake, 1978), which means the main goal is to pursue a better view and explanation rather than seek the general laws that operate in the particular case (Tsoukas, 2009).

Thus, choosing this particular case should provide empirical insights into the theoretical concepts or principles of modularity. Huoshenshan Hospital provides an example of a rapidly deployed healthcare facility to increase capacity to cope with increased hospitalisations of COVID-19 patients in Wuhan, China. Factors like high uncertainty, constrained timelines, and complex functionality made the modular hospital design more intricate (Pan & Zhang, 2022). It is a unique opportunity to explore design activities for large-scale complex engineering. There were more than 100 companies involved in the project. On January 23, 2020, the Wuhan Government commenced the construction of Huoshenshan Hospital, spanning 33,940 square meters and 1,000 beds. Just ten days later, the hospital was completed on February 2, 2020.

3.2 Data collection and analysis

The design team for the Huoshenshan Hospital project comprised approximately 60 employees from the General Institute of Architectural Design and Research Co., Ltd. (CITIC), comprising five design specialisations: architectural design, structural engineering, water supply and drainage, Heating, Ventilation and Air Conditioning (HVAC), and electrical engineering. The junior designers reported their progress to their respective leaders, who oversaw the primary flow of information within their respective specialisations. As such, this research sought to interview senior design leaders and junior designers to understand their interdisciplinary teamwork and design activities, with a written invitation and a schematic presentation of questions (see Table 1). A total of 18 interviews were conducted online (see Table 2), each lasting between 30 and 60 minutes.

Table. 1. Interview questions

No.	Questions
1	Could you describe the project, including your role and responsibilities?
2	Could you describe the required outcomes, especially regarding manufacturability and assemblability?
3	Could you describe the strategies to improve Design for Manufacture and Assembly (DfMA)? How were these strategies integrated?
4	Who was involved in the design stage? What should design and construction team integration look like? Were there any specific digital techniques that made it possible, such as BIM?
5	Could you describe the design evaluation approaches used in this project?
6	Could you describe the decision-making process of design? Who was involved in the decision-making?
7	Could you describe the challenges to DfMA? Were there any digital advancements to the application of DFMA?
8	Are there any lessons that you would take on to the next project?
9	Are there any important experiences or opinions about the project that you want to add?

Table. 2. Sample of interviewees

Code	Specialisation	Role	Working years
C1	Architectural design	Leader	> 16
C2		Designing principal	> 16
C3		On-site designer	11-15
C4		Designer	6-10
C5	Structural engineering	Leader	> 16
C6			> 16
C7		Designing principal	> 16
C8	Water supply and drainage	Leader	> 16
C9		Designing principal	> 16
C10		Designer	11-15
C11			11-15
C12			6-10
C13	HVAC	Leader	> 16
C14		Designing principal	> 16
C15		Designer	11-15
C16	Electrical engineering	Leader	> 16
C17		Designing principal	> 16
C18		Designer	> 16

Semi-structured interviews were supplemented with various other data sources in a mixed-method approach, enhancing data validation and triangulation. In the initial stage, diverse resources were scrutinised to acquire foundational information about the project case and the design institute. This research used the China National Knowledge Infrastructure to download all Huoshenshan-related Chinese reports, news, and technical analyses, which provided crucial knowledge and comprehension about the project. Subsequently, two authors facilitated a focus group discussion with CITIC to gain insights into their conventional practices, which furnished a context for comprehending the distinctiveness of Huoshenshan Hospital. In the final stage, recently published documents were reviewed, such as an official publication detailing the technical intricacies of Huoshenshan Hospital.

The research content was ultimately examined and discussed with the designers to establish a triangulated validation.

In an interpretive case study, data presentation characteristics encompass: (1) forming dynamic relationships between secondary concepts in data structures; (2) converting static data structures into dynamic grounded theoretical models; (3) literature dialogue, refining the representation of emerging concepts and their relationships. Interpretive case studies reflect the process of theoretical induction by emphasizing the encoding process of concepts. A data-driven (inductive) coding process was adopted and implemented (Saldaña, 2021). Researchers systematically presented first-order coding (analysed using respondent-centred terms and items) and second-order coding (analysed using researcher-centred concepts, themes, and dimensions, specifically looking out for concepts not present in the literature) to provide a basis for the concepts and theories that eventually emerge.

Content-driven thematic analysis was used to obtain meaning from the interview data (Morse, 1994) using Atlas-ti 9 qualitative data analysis tool. The analytical technique follows a general phenomenological approach where data was evaluated to identify significant statements and sentences that provide an understanding of how participants experienced the phenomenon (Creswell & Poth, 2016). In line with the procedure for thematic analysis, the coding scheme and final categorisation of identified factors were based on dominant themes that emerged from the interview scripts. The coding scheme enhanced the identification of key design attributes, strategies, and four categories of measures for modularity, including product, process, organisational and supply chain modularity.

4. Results

4.1 Product modularity in Huoshenshan Hospital

The design process of Huoshenshan Hospital embodied the idea of product modularity in many ways. This research categorises product modularity measures into two main areas: function proximity and component proximity (see Table 3). Function proximity is the closeness of the modules within a product or system structure, of which there are three: partitioning of building layouts, partitioning of hygiene layout, and partitioning of the site layout. For example, the site also posed a challenge to designers due to the multiple construction teams working in parallel. They had to design and strategize for multiple parallel construction situations before construction work started. Given the site's sloped nature, designers segmented it into two terraces, or modules and also divided the building into two major parts according to the site, leaving sufficient spacing at the junction and connecting only with access roads (i.e. interfaces). The height difference between the two terraces was later adjusted several times according to the construction conditions but without any impact on the overall design.

Component proximity means the physical closeness of the modules within a product or system structure. There are three ways to achieve component proximity: keeping the same type of components/equipment used in one area, using modular building components/equipment (see Figure 2), and minimised equipment-to-building interfaces and openings. Rather than consistently employing a standardised interface for product modularity, the design often opted for a non-standardised interface strategy to increase design variability, improve construction fault tolerance, and reduce construction workloads. For example, the designers built different seam widths at the interfaces at the container joints to handle construction errors.

Table. 3. Product modularity in Huoshenshan Hospital

Code/super codes	**Second Code**
Function proximity (i.e. functional closeness of the modules within a product or system structure)	Partition of building layout
	Partition of hygiene layout
	Partition of site layout
Component proximity (i.e. physical closeness of the modules within a product or system structure)	The same type of components/equipment used in one area
	Use of modular building components/equipment
	Reduced equipment-to-building interfaces and openings

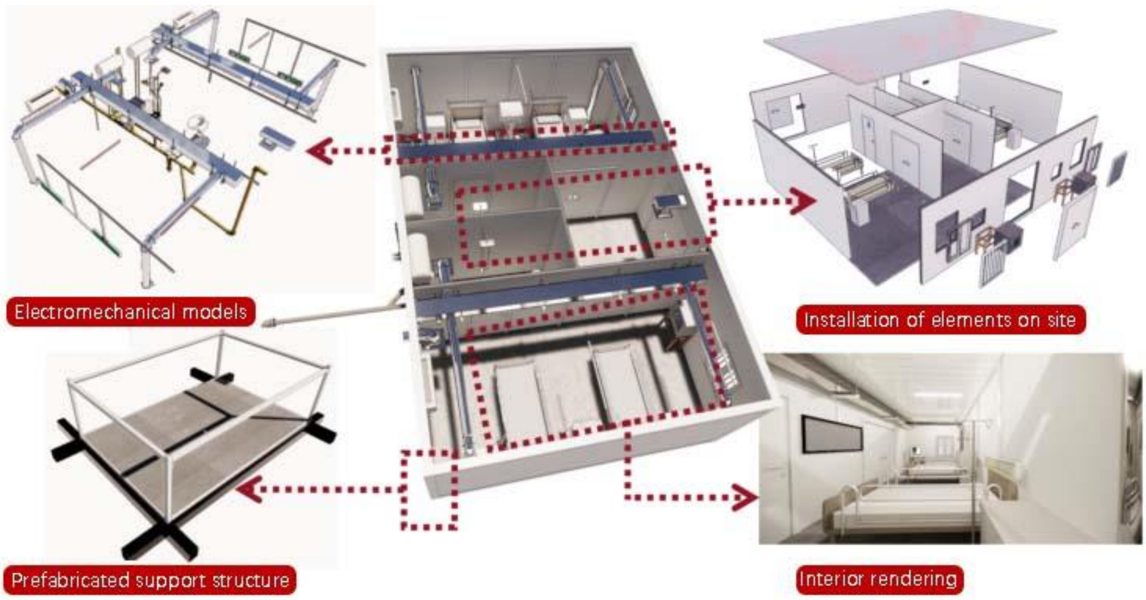

Fig. 2. Modular building components and equipment (source: CITIC)

4.2 Process modularity in Huoshenshan Hospital

Huoshenshan Hospital's design incorporated process modularity using two key characteristics: task proximity and technological proximity (see Table 4). Task proximity was the degree to which different tasks or activities within a process were related or interconnected. For example, design professionals utilized a simultaneous design-proofreading-reviewing process, where three individuals collaborated on one computer monitor, concurrently tackling all three tasks. Additionally, the hospital's entire functional space underwent standardisation. This was achieved by delineating complex medical processes, classifying functional rooms, optimising mechanical and electrical systems, and integrating equipment and pipelines, thus realizing standardised design tasks. Then, the corresponding generalised and modularized design tasks were carried out using the selected materials and electromechanical equipment. Figure 3 shows the concurrent and interrelated construction tasks for the realisation of Huoshenshan Hospital design, which also reflects the process modularity.

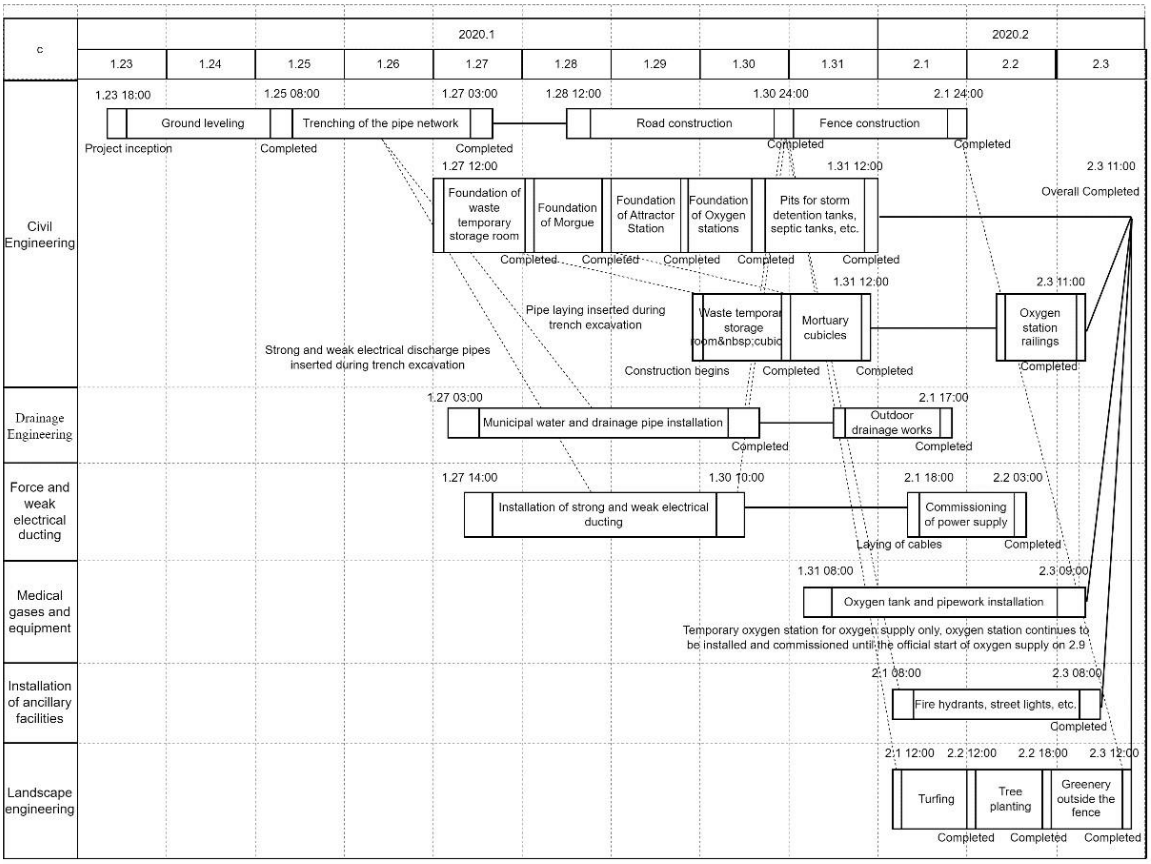

Fig. 3. Concurrent and interrelated construction tasks

Technological proximity refers to the extent to which various modules or process components share technologies or technical infrastructure. The construction team appointed technicians to participate in the design process. Moreover, the procurement team relayed feedback on available equipment and materials to the designers, guiding them to adhere to the principle of ‘use what is available’. The material specifications of different manufacturers varied, so it was necessary to deepen the design according to the actual size of the products. The design team also appointed a designer to be on-site to guide the construction according to the design, and provide feedback to the design team. The design of the prefabricated components, and the module production and processing drawings of the construction side, were carried out simultaneously, and the production and assembly process requirements were fed back to the design team in a timely manner, which then leveraged the synergy between design and factory production, professional suppliers, and on-site assembly, and provided a fundamental guarantee for shortening the construction period.

Table. 4. Process modularity in Huoshenshan Hospital

Code/super codes	Second Code
Task proximity (i.e. the degree to which different tasks or activities within a process are related or interconnected)	Concurrent design process between interdisciplinary teams
	Standardised/modularised design tasks
Technological proximity (i.e. the degree to which different modules or components of a process share common technologies or technical infrastructure)	Collaborative design process involving manufacturers
	Collaborative design process involving purchasers/suppliers
	Collaborative design process involving contractors

4.3 Organisational modularity in Huoshenshan Hospital

Three project organisation strategies were identified by three codes: responsibility proximity, knowledge proximity, and resource proximity (see Table 5). Responsibility proximity indicates the degree to which individuals or teams within an organisation share common responsibilities. The complexity of healthcare buildings and engineering systems for handling infectious diseases further increased the challenges associated with a modular design. This project involved many technical and design disciplines, far exceeding those required for ordinary buildings. Firstly, design members from different institutes collaboratively worked together. All disciplines of the CITIC had corresponding designers from contractors to work in the design office for the same design activities, and all contractor design disciplines had corresponding designers from the CITIC to work on-site together (see Figure 4). This hybrid structure promoted the sharing of common responsibilities between temporary organisations.

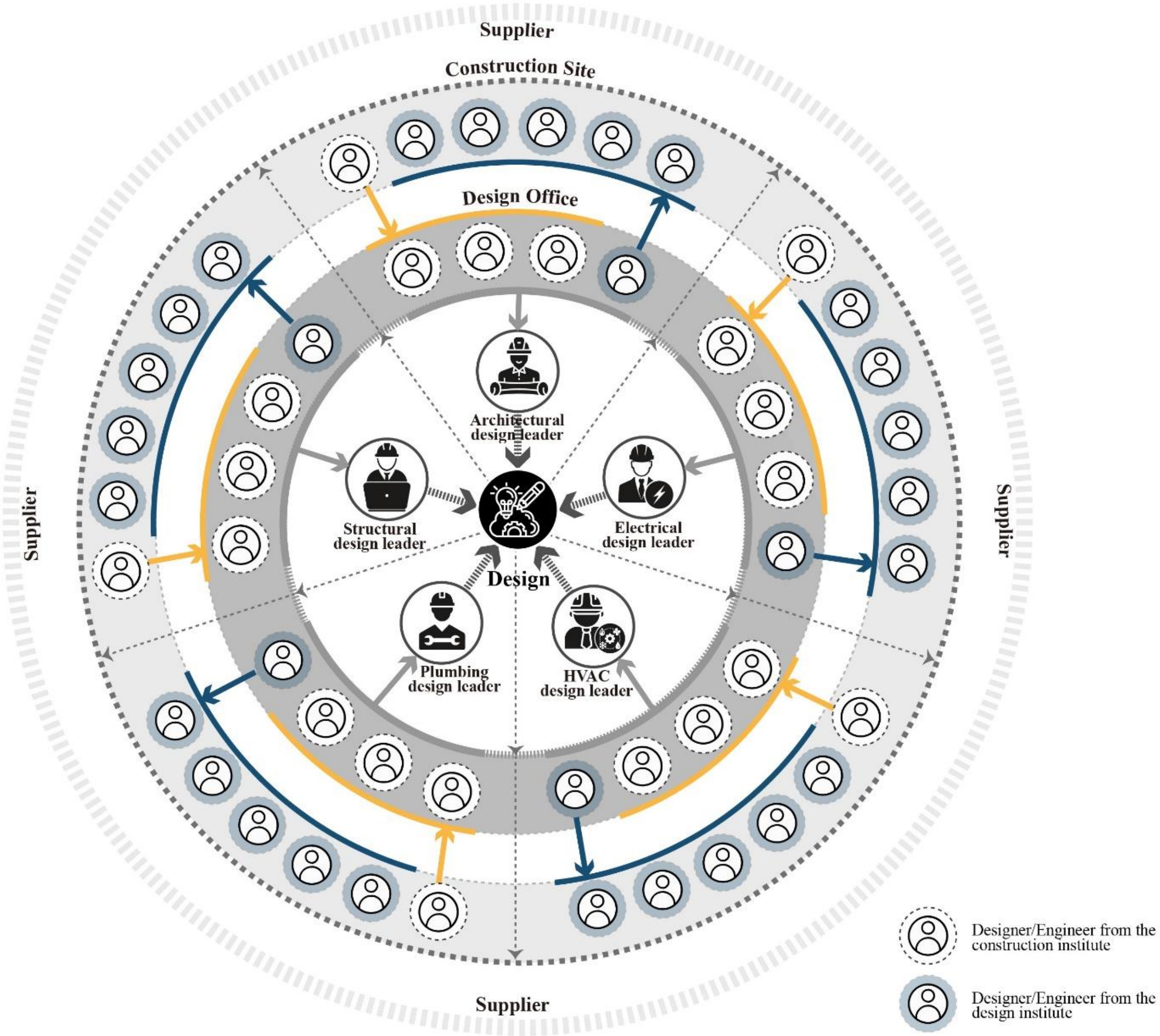

Fig. 4. Collaborative design between CITIC and contractor teams

Knowledge proximity indicates the degree to which different individuals or teams within an organisation share common knowledge or expertise. Clear communication and swift knowledge sharing between designers from various institutions were essential to the project's success. For example, a 24-hour shift schedule, high-density information exchange, daily meetings and decision-making were all adopted. Advanced design and communication technologies, such as Building Information Modelling (BIM) software, were not used at the design stage. Collaboration was achieved through conventional methods, including telephone and WeChat group communication, sharing screenshots and pictures, and SketchUp/AutoCAD drawings. All the designers boasted extensive work experience and a history of long-term collaboration. The CITIC and main contractor were all local companies with long-term cooperative relations, contributing to the collaboration speed to share common knowledge or expertise.

Table. 5. Organisational modularity in Huoshenshan Hospital

Code/super codes	Second Codes
Responsibility proximity (i.e. the degree to which individuals or teams within an organisation share common responsibilities)	Different design professionals all have designers from the main contractor
	Different design professionals all have on-site designers
	Purchase team members work with designers directly
	Collaborative decision-making to minimise changes
Knowledge proximity (i.e. the degree to which different individuals or teams within an organisation share common knowledge or expertise)	Different design professionals all have potential design interfaces for other professionals
	Work in double shifts (24*7)
	Instant online communication and daily meetings
Resource proximity (i.e. the degree to which different individuals or teams of an organisation share common resources)	Design professionals work with contractors on-site and share common on-site resources
	Contractors work with design professionals in the design office and share common office resources

Resource proximity indicates the degree to which different individuals or teams of an organisation share common resources. There were many pieces of evidence from this project about high resource proximity; for example, construction began on the site from the moment the design started; the on-site designers worked with contractors at the construction site and created on-site designs based on actual construction situations; and the contractor was involved in the early decision-making with design institutes, the government, and healthcare operators. Different design professionals from the main contractor worked directly at the design institute's office.

4.4 Supply chain modularity in Huoshenshan Hospital

The design of Huoshenshan Hospital embodied supply chain modularity in three ways, namely geographic, organisational, and cultural proximity. While geographic proximity can be measured by physical distance, time was a key indicator for Huoshenshan Hospital project. For example, the design only selected equipment and building materials that were close at hand and could be transported to the site quickly. In addition, due to the Spring Festival, the project team only brought in personnel from Wuhan to quickly build temporary teams.

Organisational proximity encompasses elements like ownership, managerial oversight, as well as interpersonal and inter-team dependencies. In this case, three main approaches represented organisational proximity: collaborative alliance, central or state-owned enterprises, and government organisations (see Table 6). For example, the design and construction companies were mainly central or state-owned enterprises. The Party Committee spearheaded numerous project promotion meetings on-site, supervising the project, guiding on-field construction, resolving critical challenges, and ensuring the project's timely completion. Many specialized companies working under the China State Construction Engineering Corporation (CSCEC) quickly participated and embedded in the specific business aspects of the construction of Huoshenshan Hospital. Represented by the China Construction Third Engineering Bureau Co. Ltd., the main impetus for the close collaboration of its subordinate enterprises and sister engineering bureaus came from the top-down internal authority of the enterprise.

The main close collaboration impetus between CSCEC and other sister central enterprises came from the administrative power of the State-owned Assets Supervision and Administration Commission of the State Council. Cultural proximity captures the commonality of language, business mores, ethical standards, and laws, among other elements. The supply chain collaboration at Huoshenshan Hospital was driven by both internal and external state-owned enterprises, with the internal manifestation being a corporate culture with a sense of social responsibility as the core of the main body of the industrial chain, and the external manifestation showing hierarchical characteristics, from top to bottom, in the order of administrative power and internal corporate authority.

Table. 6. Supply chain modularity in Huoshenshan Hospital

Code/super codes	Second Code
Geographic proximity (i.e. the physical distance between different entities within a supply chain)	Local sourcing for equipment and building materials
	Temporary local teams
Organisational proximity (i.e. the degree of closeness between these entities in terms of organisational structure or relationships)	Collaborative alliances
	Central or state-owned enterprises
	Government organisations
Cultural proximity (i.e. the degree of closeness between different entities in terms of their cultural norms, values, beliefs, and practices)	Culture of state-owned enterprises
	Culture of China's communist party
	Corporate social responsibility

5. Discussion

5.1 Modular alignment relationship

Existing studies explored and tested the alignment relationships (Da Rocha & Kemmer, 2018; Gokpinar et al., 2010; Pero et al., 2010; Sosa et al., 2004; Tan et al., 2021; Voordijk et al., 2006), such as the relationship between modular product and modular process/organisation. This case study built upon the previous research and focused on how, in the field of design, these alignments are achieved.

The investigation of the Huoshenshan Hospital case revealed two discernible alignment patterns. The first pattern, termed 'synchronised alignment', revealed a single strategy impacting multiple modularity dimensions simultaneously, as shown in Figure 5. The second pattern identified is that different strategies can act on different dimensions of modularity, referred to as 'asynchronous alignment', as shown in Figure 6. For example, see Table 7, in the alignment between process and organisational modularity, a typical strategy in the design process at Huoshenshan Hospital was concurrent processes for design and review. Given the urgency of the project and the limited time available for design, the conventional iterated design activities, which involve initial design followed by review and then final approval, can make one iteration cycle highly complex and time-consuming. Thus, a modular and concurrent approach to these design activities reduces the complexity brought about by the normal iterative process. In addition, the construction team of the main contractor had corresponding engineers involved in the design process, and the design team of the design institute had designers involved at the construction site (see Figure 4). The traditional iterative process of design activities between design organisations and construction organisations has been transformed in such a way that human resources, information and knowledge are exchanged in a modular and concurrent approach. This not only reduces the iterative process and complexity but also addresses the constraints of design timelines and construction schedules. Complexities existed in both design processes and design organisations. This synchronised alignment to collaboration not only reshaped processes and drove modularity in design processes, but also reshaped the organisational relationships.

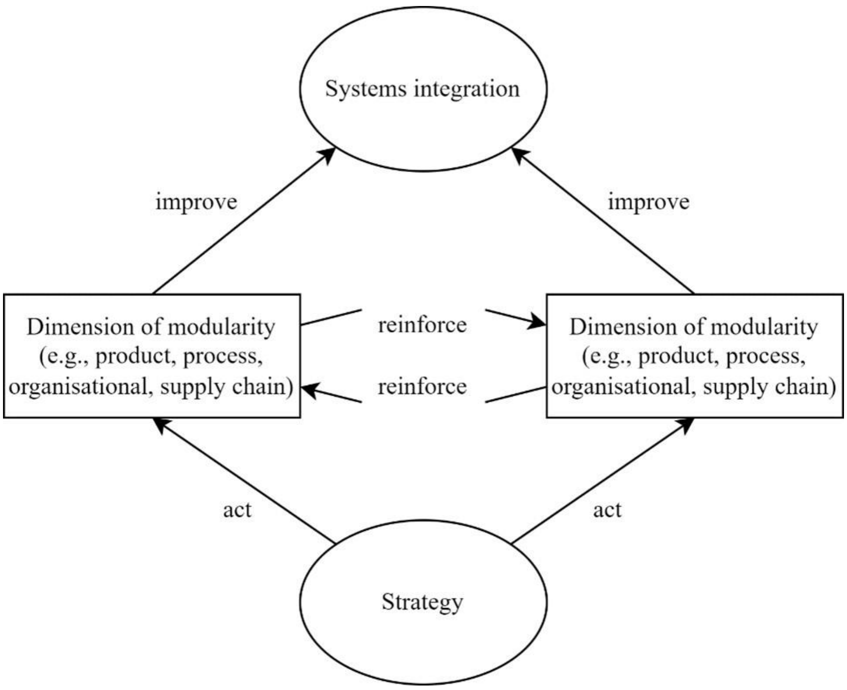

Fig. 5. Modular alignment relationship through the same strategy (i.e. synchronised alignment)

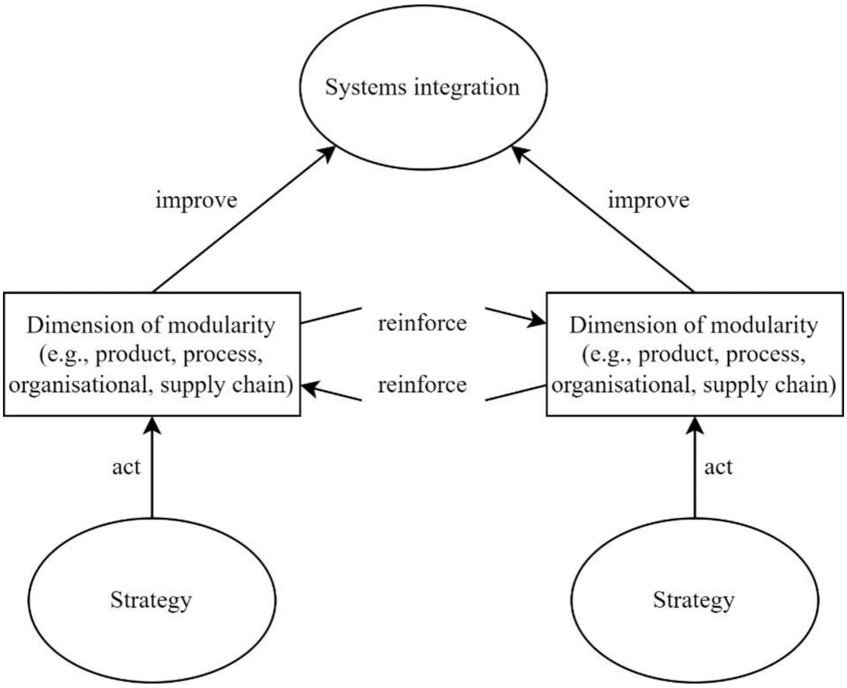

Fig. 6. Modular alignment relationship through different strategies (i.e. asynchronous alignment)

Table. 7. Examples of modular alignment relationships

Types	**Examples**
Synchronised alignment	Organisational modularity: Different design disciplines all have designers from the main contractor (+responsibility proximity)
	Process modularity: Concurrent design process between interdisciplinary teams (+task proximity)
Asynchronous alignment	Supply chain modularity: Collaborative alliance (+organisational proximity)
	Process modularity: Collaborative design process by involving purchasers/suppliers (+technological proximity)

Note: '+' means the increase of modularity level

In a contrasting alignment type termed 'asynchronous alignment', varied strategies targeted distinct modularity dimensions, mutually reinforcing one another. For example, in each of the seven building systems at Huoshenshan Hospital, designers applied the strategy of process modularity to achieve concurrent design and engineering by using off-the-shelf components for shortening construction duration, which is associated with supply chain coordination. Utilising readily available goods from suppliers permits quick procurement and immediate construction. Established relationships between designers and suppliers streamline the supply chain, facilitating faster coordination and acquisition. Thus, the construction of each building system was achieved not only by the design process but also through the coordination of the supply chain. The process's modularity corresponded to the supply chain's modularity but was achieved through different measures. The former relied on task management measures of the designer, while the latter relied on modularity achieved by strategies based on geography, organisation, and culture. Instead of aligning strategies during the modularisation process, different strategies were reinforced after the modularisation process.

5.2 Modular complementarity relationship

Potential drawbacks of modularity, such as the unwillingness or inability to cooperate due to internal specialisation (Tee et al., 2019), were confirmed in this case study, in that not all sub-systems of buildings were conducive to a reduction of complexity through modularity principles. Fundamentally, it is the critique of holism against reductionism, which argues that all parts of a system (e.g., the universe, the human body, etc.) are an organic whole and cannot be separated or understood separately. A compromise between holism and reductionism seems necessary. In contrast to existing work perceiving modular strategies and integral strategies as opposites, Tee et al. (2019) argue that they can be complementary for collaboration at an inter-organisational level. In Huoshenshan Hospital case, when complexity could not be simplified using one approach (i.e. mono-dimensional modularity strategy), such as product modularity, it was tackled using other methods, like process and organisational modularity. This multi-dimensional modularity relationship is termed the 'modular complementarity relationship'.

This type of relationship is broadly divided into two categories. The first is one in which integration in a particular system is facilitated by sacrificing a certain level of modularity so that it has a lower level of modularity compared to other dimensions (i.e. subtraction complement, see Table 8 and Figure 7). The cost and risk of this reduced degree of modularity are addressed by modularity in other dimensions. For example, regarding product modularity, instead of using standardised interfaces for retrofitting containers and adding plumbing equipment, non-standardised interfaces for construction connectors were used to improve construction fault tolerance and resilience. The observed phenomenon is due to constraints from limited timeframes. Consequently, architects and builders relied on existing inventories of materials, components, or equipment instead of producing new ones. Consequently, many sub-systems within the building cannot uniformly adopt the same type of selection due to limited stock. This necessitates the implementation of varying types of materials, components, or equipment for identical architectural sub-systems in different locations or regions. Reduced modularity in product design saved engineering time and eased construction challenges. Moreover, using non-standardised interfaces proved more effective than standardised ones when dealing with various materials, components, or equipment. The drawbacks due to the use of non-standardised interfaces were addressed through standardised measures in the process, organisational and supply chain dimensions. For example, the local sourcing for equipment and building materials can be considered as geographic proximity to represent the strategy of modularity of the supply chain. Without local proximate sourcing, the project cannot be accomplished. Consequently, non-standardised product interfaces and localised procurement strategically complement each other's strengths and weaknesses.

The second is a relationship with one dimension that has a higher degree of modularity compared to other dimensions (i.e. addition complement, see Table 8 and Figure 8), thus making it more conducive to solving a particular problem. Again, the benefits of this non-alignment outweighed the negative effects, which allowed the reinforcement between dimensions to be established. Similar to the scenario mentioned in the subtraction complement example, different configurations of products (i.e. materials, components, or equipment) were employed to achieve the same function at various installation sites to address the inadequacy of some of the singular types of products. A strategy of product modularity seeks to achieve standardisation within a site area's products. In the same site area, products with identical configurations are employed. This, in turn, facilitates the management and reduction of complexities arising from non-standardised processes inherent in diverse configurations of products.

Table. 8. Examples of modular complementarity relationships

Types	Examples
Subtraction complement	Product modularity: non-standardised interfaces (-component proximity)
	Process modularity: Standardised/modularised design tasks (tasks proximity)
	Supply chain modularity: Local sourcing for equipment and building materials (geographic proximity)

Addition complement	Product modularity: Same type of components/equipment used in one area (+component proximity)
	Process modularity: non-standardised process for non-standardised products (task proximity)

Note: ‘+’ means the increase of modularity level; ‘-‘ means the decrease of modularity level

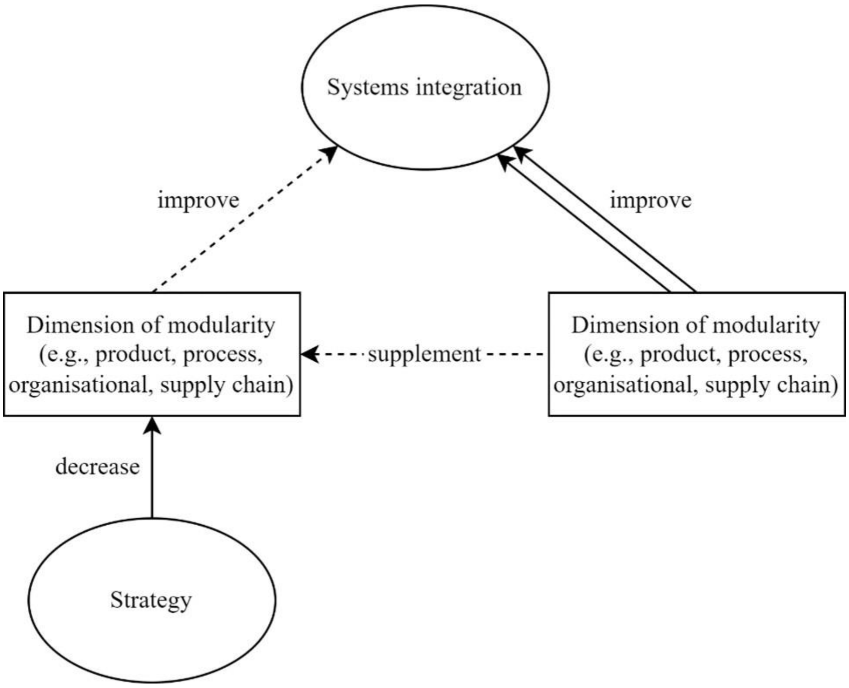

Fig. 7. Modular complementarity relationship through the decrease of modularity (i.e. subtraction complement)

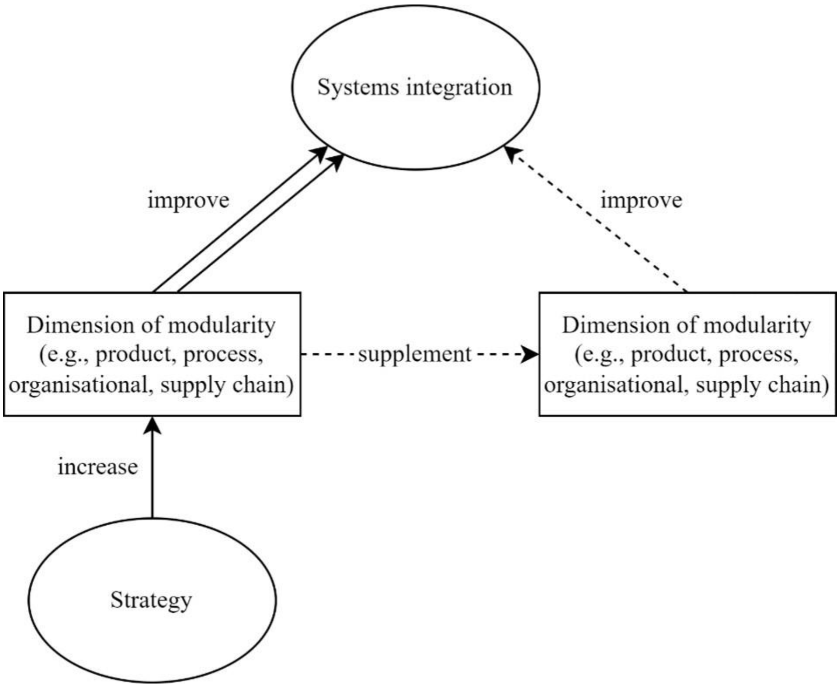

Fig. 8. Modular complementarity relationship through the increase of modularity (i.e. addition complement)

The modular complementarity relationship confirms research arguments suggesting that alignment between modular dimensions is not always present. Instead, there are specific scenarios in which alignment needs to be broken to solve a very salient problem. The modular complementarity relationship can address complexities across multiple modularity dimensions. In a broader perspective, this type of reinforcement relationship underscores the importance of flexibility in modular design and strategy. While modularity offers numerous advantages, its application should be context-specific. Decision-makers should be ready to employ a mix of modular and integral strategies based on the unique demands of the project and the problems at hand. In this sense, the Huoshenshan Hospital case serves as a testament to the adaptability of modular principles in the face of real-world complexities.

5.3 Modular incentive relationship

In addition to the two relationships described above, there was a third relationship between multiple dimensions of modularity called the modular incentive relationship (see Figure 9). Incentivisation in one dimension of modularity indirectly influences corresponding resources in another dimension, creating a reinforcement or matching strategy. However, two modular dimensions reinforced one another indirectly only when corresponding resources or matching strategies were available.

There was an incentive relationship between product modularity and organisational modularity in using digital communication technology. The organisation was motivated to adopt modularity due to the requirements of numerous building product information. For example, various WeChat groups were established for organising teams for different design tasks. The hierarchy of information was transformed in the process. Abstraction, information hiding, and system interfaces between different sub-systems were implemented to different degrees in the case study. From the micro to the macro, hierarchical relationships between different architectural components, or dimensions, were developed differently. Compared to the modular alignment and the modular complement types of relationships, the modular incentive type of relationship was loosely-coupled and less direct, and its implementation was dependent upon corresponding resources and matching strategies. In general, the incentive relationship relied on an indirect reinforcement of modularity in another dimension through incentives.

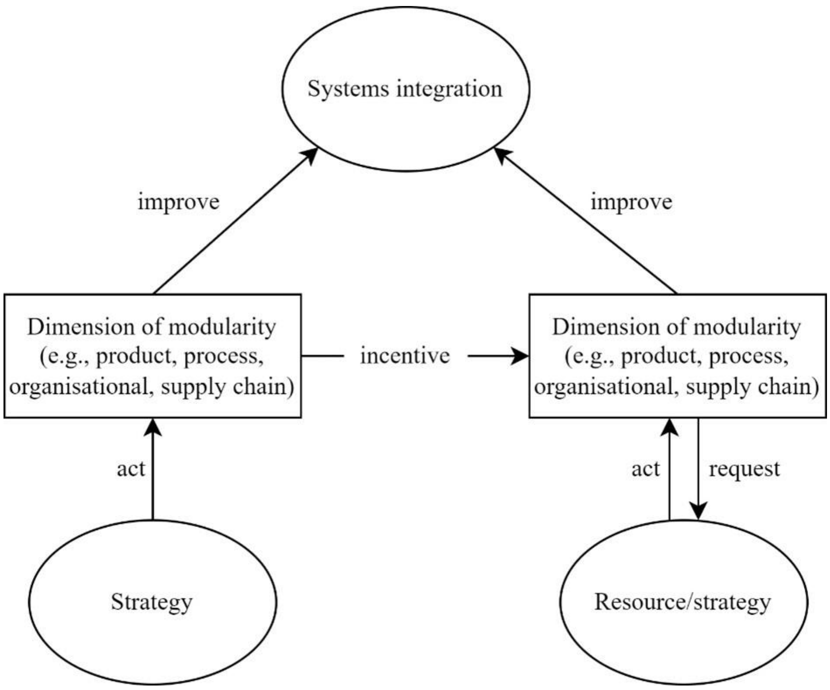

Fig. 9. Modular incentive relationship

The use of digital technology, especially BIM, in the DfMA process might illustrate an alternative incentive-type of relationship. However, Huoshenshan Hospital did not adopt BIM tools in the design process because of insufficient resources (e.g., time) and suitable strategies to manage this deficiency.

Thus, for the application of BIM tools, neither incentive, modular alignment, nor modular complementarity relationships were formed between product modularity and organisational modularity.

5.4 Capabilities of reinforcement relationships for design

There is no one-for-all alignment or misalignment relationship that can achieve systems integration of engineering design. The large-scale engineering design process and its outcomes (i.e. artefacts) constitute a dynamically evolving hierarchical system, with submodules that are difficult to define in a general manner and should be specific to the project, as emphasised by Da Rocha and Kemmer (2018) in their research on the dynamic nature of modules in construction engineering. Based on this definition, the relationships between modules across these four dimensions not only change due to non-consistent definitions of modules but also present different dynamic relationships at different hierarchical levels due to the dynamic system structure. This is one of the potential reasons for the debates regarding multi-dimensional modularity alignment and misalignment. This research advances Kusiak's (2002) thinking on the coordination of product, process, and resource in engineering design and proposes that reinforcement relationships can reconcile the debate between modular alignment and misalignment relationships. This research suggests that whether the relationship is alignment or misalignment is only a temporary and formal manifestation of modularisation at different levels of engineering systems and not the true reason for reducing complexity and systems integration. The essence lies in whether a mutually reinforcing relationship occurs. When reinforcement occurs across product, process, organization, and supply chain dimensions, resources are directed to where they can best solve sub-system complexity, and the mutually reinforcing adjustment of dependence and independence between different submodules achieves a reduction in complexity strategy. This process reinforces rather than questions and resists the reduction of local design complexity.

This research, using the one-off large-scale engineering project of Huoshenshan Hospital as a unique case, does not intend to propose a comprehensive relationship framework. The three identified co-existence/combination relationships of various dimensions of modularity do not necessarily represent a comprehensive and universally applicable scenario in all engineering designs. Rather, they offer a new perspective on product modularisation strategy by coordinating the reinforcement relationships of process, organisation, and supply chain, and reconfiguring them as relationships of alignment, complementarity, and incentive. This research identifies how multi-dimensional modularity can be used to simplify systems and reduce complexity, and enriches the understanding of the multi-level systems framework of modularisation emphasised by Pan et al. (2019). From a single modularity perspective, the reconfiguration of abstraction, information hiding, and interfaces is an essential strategy for modularising a traditional product, process, organisation or supply chain. However, highly abstracted modules, which conceal information and have reconfigured interfaces, are resource-intensive and pose challenges across all sub-systems of the four dimensions. In Huoshenshan Hospital, due to limited resources, reconfiguration cannot achieve highly modularised standardisation at all interfaces in all scenarios across the four dimensions. The reinforcement relationship led to dimensional coordination and better use of modularity, which in turn reduced complexity, and was a strategy to manage design limitations and design process challenges.

5.5 Limitations and future research

Healthcare construction is a highly complex and dynamic engineering system. This research used qualitative data for a single case study in the context of COVID-19 in China, which was unique and different from the setting for most major general healthcare construction projects. Consequently, this study may have limitations regarding the number and selection of cases. Future research could address these by adopting multiple cases and comparative studies. Besides addressing the limitations of this study, future work can further explore and advance modularity. Researchers could further incorporate digital-enabled approaches into the research of modularity. The case selection did not represent state-of-the-art practices in terms of the use of digital tools. As new technologies emerge, such as digital twins, blockchain and artificial intelligence, approaches to design will change dramatically; however, the combination of modularity and these emerging technologies in design activities has not yet been fully examined.

6. Conclusion

The study identified ten factors (i.e. proximities) that impact the perception of the four dimensions of modularity (across organisation-process-product-supply chain dimensions), along with three types of reinforcement relationships to minimise design complexity. These relationships comprise modular alignment, which includes both synchronised and asynchronous alignment, modular complement, encompassing both subtraction and addition complements, and modular incentive relationships. For these three reinforcement relationships, the research builds upon the knowledge of alignment relationships, specifically the mirroring hypothesis, and extends Hall et al.'s (2020) construction firm-level investigation. The research extends Tee et al.'s (2019) complementarity relationships between modular design and integration practices, and identifies modular incentive relationships. The incentivisation strategies for one modularity dimension indirectly motivate corresponding resources for another dimension, thereby creating a matching/reinforcing modularity strategy. This research found that all three reinforcement relationships that exist in organisation-process-product-supply-chain dimensions can be used to reduce complexity and facilitate systems integration. Furthermore, the research has identified two key characteristics of these reinforcement relationships. First, they can reduce the complexity of realising design. Second, they can be used to integrate various design strategies, such as eliminating the fragmented use of digital tools and design guidelines.

This research lays the foundation and bridge for the theoretical exploration of design activities by using modularity as the pathway. It investigates modularity which reduces complexity and improves building systems integration. In addition to the alignment relationship explained by the 'mirroring hypothesis', this case illustrates two types of misalignment relationships also contribute to complexity reduction, thereby offering a unique insight into understanding engineering design. Practically, this research also extends the application of modularity in the field of complex engineering projects, especially in the healthcare setting. Modularity has practical implications for two groups: design organisations and design practitioners. This research offers a roadmap for implementing modularity, and thus enhances the ability of both organisations and practitioners to manage and simplify complex engineering design activities. By referencing Wuhan's experience, the reinforcement relationships between the dimensions of product, process, organization, and supply chain are crucial for the complexity reduction in design activities.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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