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Sustainable Future-Proof Healthcare Facilities: Modular and Adaptable Design Approach

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Abstract: The challenge of implementing industrialized construction to achieve sustainable future-proof healthcare facilities is not only about construction methods themselves but also about how to shift design methodologies. COVID-19 has raised the attention of research and practices in using modular design and construction for healthcare facilities. However, the lifespan and functional differences between general and emergency healthcare facilities mean that their sustainable design requirements are not exactly the same. Drawing from 27 interviews and design review sessions with 19 international groups of experts, this research proposes a modular adaptable hospital design (MAHD) approach based on the Open Building Concept (OBC). This includes an evaluation framework composed of five design categories and 23 subcategories complemented with a set of design guidelines and it concludes by identifying a future implementation pathway. This research extends the implementation of OBC through theoretical contributions for modular and adaptable designs and practical guidelines for future design implementation. **DOI: 10.1061/JMENEA.MEENG-5942.** *© 2024 American Society of Civil Engineers.*

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Introduction

Aging demographics, technological transformations, and shifting medical needs are intensifying the challenges in the built environment of healthcare facilities where medical and health services are provided, such as hospitals, clinics, and nursing homes. The physical infrastructure of healthcare facilities directly influences the capability of healthcare providers and patient satisfaction, subsequently affecting the utilization of health services (Anåker et al. 2017; Xin et al. 2024). However, poor healthcare facilities are hindering these services. In 2021, the World Bank and World Health Organization (WHO 2021) indicated in their report that our world is off track in achieving the sustainable development goals (SDGs) for universal health coverage. These challenges urge practitioners to think about how sustainable design can be implemented to alter this situation.

The design of healthcare facilities faces unique challenges in achieving SDGs. Two of these include complex design requirements and potential future changes. First, the healthcare facility is one of the most complex types of building infrastructure (Verderber 2010). Its design presents intricate functional challenges, particularly given that many of these establishments are expected to function beyond their anticipated 50-year life cycle (Wagenaar et al. 2018). Second, there is a high demand for long-lasting healthcare facilities that can constantly adapt to changing trends, including new medical procedures, technologies, changing government regulations, or new demographics (Schmidt and Austin 2016). Healthcare facilities often undergo significant renovations over a building's lifetime (Carthey et al. 2010). Thus, practitioners and scholars see the need for flexible and resilient design principles for these facilities.

One approach to solving this problem is to apply future-proofing engineering in design. For example, Memari et al. (2022, 2023) established a conceptualization of future proofing in healthcare facility design via a taxonomic hierarchy and an interdisciplinary approach. Regarding design strategies, Karlsson et al. (2021) examined the ways Swedish architects incorporate future proofing into healthcare facility design. They found 16 distinct design strategies aimed at addressing potential future changes. However, the background of these design strategies is based on conventional on-site healthcare construction. With the transformation toward industrialized construction, Masood et al. (2016) highlighted using modular and adaptable design strategies to achieve future-proof building facilities. Lawson et al. (2014) categorized different modular design features and requirements of healthcare facilities. Tan et al. (2021) investigated modularity strategies in the design of COVID-19 emergency modular wards. Modular design is a design approach that breaks down a system into smaller parts called modules, which can be independently created, modified, tested, and reused (Baldwin et al. 2000). Modular design is a key strategy in future-proofing engineering, as it allows for easy updates and adaptations to new technologies or requirements without overhauling the entire system (Gil 2009). However, these existing studies mainly focus on design strategies and buildability for current needs but not on future-proofing engineering and design strategies responding to medium- and long-term changes.

After COVID-19, how to deal with these widely constructed emergency temporary modular wards has become a thorny issue

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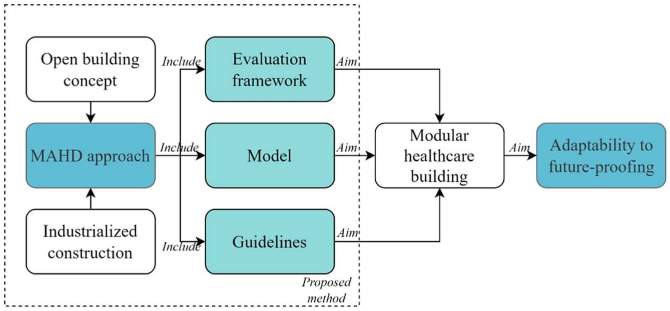

Fig. 1. Relationships between key concepts.

in some countries, such as China. In addition to temporary modular emergency healthcare facilities, research into design for general, nonemergency healthcare facilities also urgently needs to be prioritized. Baldwin et al. (2000) also point out challenges in modular design, including ensuring standardization of interfaces, managing dependencies between modules, and maintaining the performance and coherence of the overall system while pursuing modularity. There is a clear research gap in understanding modular and adaptable design strategies for healthcare facilities under the context of general, nonemergency healthcare facilities built with industrialized construction. Specific recommendations and guidelines relating to future-proofing engineering remain absent.

This research focuses on the design for construction rather than the construction itself. Modular design and modular construction are two different concepts. The former has been used in many areas, including both the manufacturing and construction industries, as discussed by Baldwin et al. (2000) and Tan et al. (2024). However, the latter concept, namely modular construction, is only used in the construction industry. Modular design could also be used for nonmodular construction, and they could be misaligned (Tan et al. 2024). This research responds by proposing an initial framework and design guidelines for a modular adaptable hospital design (MAHD) approach (see Fig. 1). It integrates modular and adaptable design with industrialized construction principles, which have been developed for healthcare facilities. It enriches the academic discourse on system separation and modularity in healthcare facility design and provides practical guidelines for architects and planners. This research commences with a literature review, introducing how the Open Building Concept (OBC) and industrialized construction can be integrated into strategies for healthcare facility design and highlighting existing research gaps. Section "Methodology" delineates the specific research methodology employed. Subsequently, "Findings" section presents the main findings of the study, encompassing three primary tools: the evaluation framework, model, and guidelines. These facets are discussed individually in the section "Discussions," and the research concludes in the section "Conclusions," offering directions for future research.

Literature Review

Open Building Concept in Healthcare

The principle of clear separation of the building components according to their expected lifespan has been outlined as one of the most prominent techniques for increasing the flexibility and adaptability of healthcare facilities (Schmidt and Austin 2016), and it was further developed under the umbrella of the OBC. The OBC can be defined as a method of building design that is "open for change and prepared to adapt to many ways of use to extend their lifespan by combining a robust and resilient structural framework ("carrier" or "support") with reusable (renewable or recycled) infill systems that are designed for disassembly, such as facades, interior walls, fixed furniture and technical facilities" (Kendall 1999). Several studies have proven that the OBC-oriented design guidelines are effective in increasing the flexibility and adaptability of healthcare facilities (Kendall 2018; Pilosof and Kalay 2017; Pilosof 2021), thus it could be a solution to achieving future-proof healthcare facilities. One of the earliest examples where the OBC was employed as a primary design principle was in 2005 for the 50,000 sqm INO Addition for the Insel Hospital in Bern, Switzerland (Kendall 2005). Since then, OBC principles have been applied in other healthcare facility designs.

Some OBC-oriented design strategies have been identified in healthcare architecture. In a comparative case study conducted, Pilosof (2021) uncovered a design strategy for constructing a versatile "container" capable of integrating future medical programs. This approach hinges on differentiating between elements that are likely to remain constant and those prone to change. Such strategies are foundational in the initial phase of design, a concept also echoed in the book by Kendall (2018). Similarly, Macchi (2018) emphasizes the concept of system separation as a proactive approach to building design. The guiding philosophy here is to firmly establish a limited number of elements to maintain flexibility while ensuring dependability.

Despite its alignment with the principles of modularity theory, this concept of system separation has not been fully integrated into the existing research on OBC within healthcare architecture. Furthermore, these studies predominantly abstract high-level architectural design strategies, drawing insights primarily from architects (Kendall 2018), whether in practice, research, policy-making, or a combination of these roles, and concentrating mainly on the initial stages of the design process. While the importance of multidisciplinary approaches in healthcare architecture is acknowledged, there is a notable lack of research on strategies that span multiple disciplines. Consequently, transforming initial architectural design strategies into comprehensive, life cycle–oriented engineering strategies through a multidisciplinary lens represents a significant research gap in existing studies.

Integration of Industrialized Construction in Healthcare

Recent advances in industrialized construction methods have prompted researchers to merge OBC principles with modern offsite prefabrication and modular construction techniques (Stefano et al. 2017). In healthcare facilities, modular design offers the intrinsic advantage of scalability and adaptability, allowing for rapid expansion or reconfiguration of spaces in response to changing medical technologies, patient needs, or healthcare practices. This approach significantly reduces downtime and costs associated with renovations or expansions, ensuring that healthcare services can continue to evolve and improve without major disruptions to patient care or facility operations (Tan et al. 2021, 2024). The main idea is to plan for flexibility by using varying degrees of prefabrication, from interior panels to entire rooms made as modular units. Kendall (2018) suggests categorizing systems based on how long they last: building structure, fit-out systems, and furniture and equipment. Using this, on-site construction is recommended for the primary system, while the secondary and tertiary systems use prefabricated panels and modular methods (Stefano et al. 2017). The approach shows promise for inpatient rooms and has been proven in the early development stages. However, researchers emphasize the importance of broader testing within entire hospitals and a deeper examination of its market and economic viability (Stefano et al. 2017).

In addition, there are doubts about the suitability of industrialized construction for healthcare (Assaad et al. 2022; Zhan et al. 2024), especially for complex facilities that go beyond simple wards or outpatient clinics (Pan and Zhang 2022). While adaptability is crucial in healthcare construction, industrialized construction faces challenges with incorporating last-minute design changes (Jang and Lee 2018). The challenges of integrating construction methods, such as industrialized construction, with design approaches have a long-standing history (Tatum 1989; Choi et al. 2020; Tan et al. 2020). Traditional healthcare construction often follows a tailored approach where components are uniquely designed, manufactured, and assembled for each project. Such customized manufacturing often leads to escalated costs and prolonged production timelines (Mittal et al. 2020; Tillmann et al. 2010). For the assurance of patient care, future healthcare facilities should integrate the latest insights from medical research and contemporary health technologies and be flexible to future advances and changes (Aalto et al. 2019). Yet, achieving a future-proof design remains a significant challenge.

Research on emergency healthcare facility design often targets immediate design and buildability needs, overlooking long-term adaptability, a gap highlighted by the challenge of repurposing temporary modular wards post-COVID-19 in China. This highlights the urgent need for research into future-proofing design strategies, especially for general hospitals, beyond emergency facilities. Existing studies have proposed sets of initial design guidelines to increase the level of flexibility and adaptability. These guidelines advocate for a clear component separation by lifespan and the use of expandable prefabricated and modular technologies to ensure buildings can easily adapt to future changes (Carthey et al. 2010; Carthey and Chow 2011; Schmidt and Austin 2016; Capolongo et al. 2016). However, these design guidelines are relatively general and lack specificity, making them challenging to implement in the healthcare sector due to the unique and stringent requirements of medical facilities, such as specialized spaces, strict regulatory standards, and the need for advanced technological integration. There is a gap in systematically integrating these general guidelines into a practical approach for healthcare designers. The research gap identified involves extending the concept of system separation, prevalent in current OBC in healthcare design, to the realm of modularity theory. This transition should also account for the complexities and practicalities of implementing industrialized construction methods. Such an approach is critical for aligning with the evolving trajectory of healthcare architecture. In essence, the gap signifies the need to integrate the adaptability and flexibility inherent in OBC's system separation strategy with the efficiency and standardization of industrialized construction. This integration can be informed by modularity theory, which emphasizes the design of components that can be easily interchanged and reconfigured. Addressing this gap requires a deep understanding of how these concepts can coexist and complement each other in healthcare architecture, which continuously adapts to technological advancements and changing medical needs. The research aim is to develop a design strategy that accommodates the immediate requirements of healthcare facilities and ensures their long-term sustainability and adaptability.

Methodology

Overview

The research aims to develop a preliminary framework and establish design guidelines to facilitate the incorporation of MAHD in upcoming healthcare construction initiatives. Using a qualitative research methodology allows for a deep and comprehensive exploration (Groat and Wang 2013), facilitating the uncovering of essential processes for innovation in healthcare design and construction. Some studies have used this type of methodology to establish architectural design guidelines. For example, Kyrö et al. (2019) integrated adaptability with the concept of OBC and identified three categories of adaptability strategies in healthcare architecture, including generality, flexibility, and elasticity, through 27 semi-structured interviews with designers, project managers, clients, and healthcare professionals. Thus, this research employs similar qualitative methods but for different research aims. Fig. 2 illustrates the process of research, starting with foundational desktop research and stakeholder interviews, progressing through data analysis and feedback loops, and finalizing a report of academic results that inform an industry partnership to build a pilot project in Switzerland. The case study in this research is used for illustration and validation. According to Yin (2017), the single case study is well-suited for this objective. This approach facilitates gathering detailed insights from practitioners and experts, enabling the development of MAHD approach based on the OBC that is directly applicable to the complexities and regulatory demands of medical facilities.

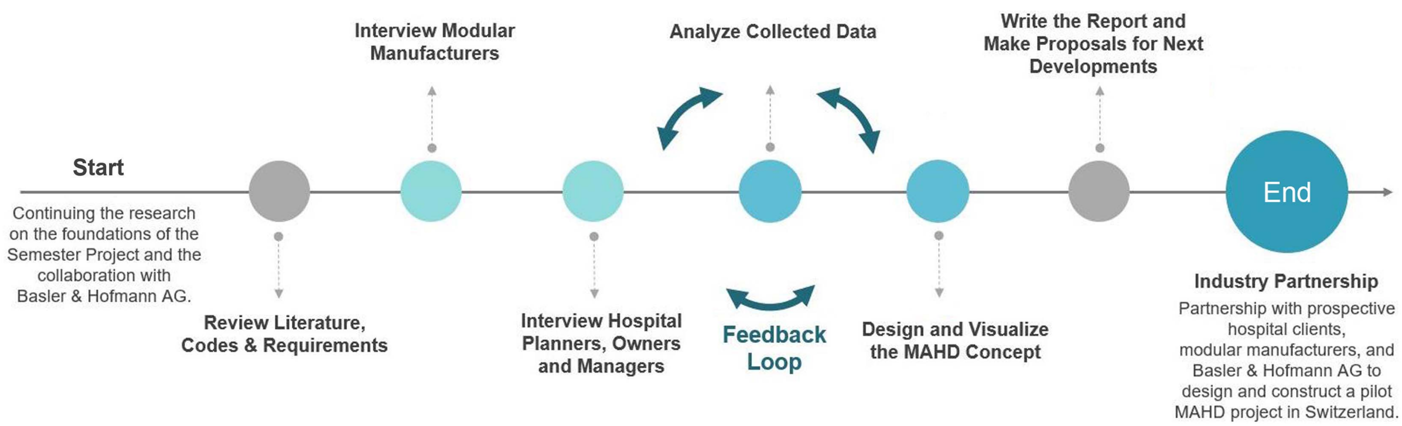

Fig. 2. Research procedures.

Data Collection

In the initial research stages, a set of interview questions was formulated by using insights from a literature review and feedback from a diverse group of stakeholders in the healthcare design, construction, and management sectors. The results were used as the basis for a more targeted literature review. The literature addressed various facets of healthcare facility design and construction, examining a wealth of resources including (1) general hospital design and construction (8 books and chapters, 21 journal articles and papers, 15 consultants' and market reports, 9 white papers and theses); (2) guidelines, laws, and regulations specific to hospital design (41 different national and international online sources reviewed); (3) user-centered and evidence-based designs (1 book, 7 journal articles and papers); (4) concepts of flexibility and adaptability in hospital design (3 books and chapters, 19 journal articles and papers, 3 white papers and theses); (5) industrialized and modular approaches (9 books and chapters, 32 journal articles and papers, 11 consultants' and market reports, 5 white papers and theses); (6) digital optimization in design and planning (17 journal articles and papers, 6 consultants' and market reports); and (7) sustainable hospital design and construction accounting (2 books and chapters, 11 journal articles and papers, 1 white papers and theses). The literature review aimed to gather knowledge on the MAHD approach, covering aspects such as its economic viability, market appeal, technical feasibility, and potential benefits compared to traditional design methods. Then, both the results of the questionnaire and the targeted literature review were used as the basis for building the "catalog of questions" used during the semistructured interviews in the next stage of the MAHD research.

Then, a total of 27 semistructured interviews and collaborative design review sessions involving various experts in the healthcare construction sector were held via online platforms. The breakdown is as follows:

- Ten interviews involve eight groups from firms specializing in the design and production of modular construction components for healthcare facilities, including Renggli AG, Etex, Erne Holzbau AG, RAD Urban, Cadolto GmbH, EIR Healthcare, Admares Ltd, and Elomatic.
- Ten design sessions were led by four architects with expertise in healthcare facility design and construction.
- Four discussions were with hospital owner representatives, including planners, managers, and investors.
- Three consultations were with architects and advisers proficient in healthcare process optimization.

These interviews, ranging from 60 min to two and a half hours, often featured multiple industry experts and covered a broad spectrum of professional perspectives and supplementary qualitative data such as technical diagrams, company reports, and product catalogs. The research utilized purposive sampling (Taherdoost 2016) to ensure a rich, diverse pool of insights. Participants from Switzerland, Continental Europe, the US, and Singapore involved in healthcare facility design and construction were chosen, with a focus on those in prefabricated and modular technologies and experts in hospital workflow optimization. All the data—including interview responses, expert opinions, and supplementary resources—were meticulously gathered and documented in a prearranged response template. The collection process ceased when over 80% of the principal subjects repeatedly surfaced in the interviews, indicating the attainment of data saturation, according to Guest et al. (2020).

Data Analysis

This research used thematic analysis for the interview transcriptions by adopting a deductive strategy and steps outlined by Nowell et al. (2017), and enhanced by insights from Castleberry and Nolen (2018). This approach combined with an extensive review of relevant guides, codes, and statutes to forge the MAHD evaluation framework and ancillary guidelines and models.

First, initial codes were generated after familiarizing with the data. Then, the next step is searching for themes. Once the codes were determined and different quotes assigned to their respective codes in NVivo version 1.0, the coded subthemes were then clustered into larger themes, as shown in Table 1.

Second, the number of quotes per coded theme was analyzed and graphed with the hierarchy of themes from the most commonly discussed to the least commonly discussed themes. The initial set of

Table 1. Total list of initial subthemes (codes) as clustered into initial larger themes

Theme	Subthemes (codes)
Costs	Feasibility analysis Initial capital investment Lifecycle costs New business models with MAHD Operative costs Planning phase Reconstruction costs
Optimal design features (user- and patient-centric)	Evidence based and people centered Flexibility and adaptability (e.g., open building concept) Health benefits Minimal reconstruction disturbances Natural light Natural ventilation Optimal process workflows Plan with different levels of prefabrication (2D versus 3D) Planning for change-of-use scenarios Social spaces and interactions Views of nature
Logistics (planning, manufacturing, transport)	(Dis)asembly of MAHD modules and system Manufacturing MAHD modules Planning of new hospital facilities Transport of MAHD modules
Technical systems and feasiblity	Facade options Fire safety Insulation (acoustics, vibrations, thermal) Materials MEP Special medical equipment Structure User safety (medical facility safety and protection)
Time (schedule)	First construction time savings Manufacturing time Planning and design time Reconstruction time savings Refurbishment time
Sustainability	Ecological–energy Ecological–materials Economic sustainability of MAHD Social–quality of MAHD hospital design (soft design aspects) Social–health benefits

Table 2. Examples of quotes that were recoded with new codes and themes

Theme	Subthemes (codes)	Exemplary quotes	Recodes
Costs	New business models with MAHD	"Work with digital twins to optimize the hospital processes and building with MAHD throughout the life cycle." Consultant Specialized in Hospital Process Optimization	Sustainability (economic sustainability of MAHD)
Time	Manufacturing time	"It takes 3–6 months to manufacture modules for a project of a hospital scope." Group of modular manufacturing experts #2	Logistics (manufacturing of MAHD systems)
Time	Reconstruction time savings	"One crane and one team can insert and connect two modules per day." Group of modular manufacturing experts #7	Costs (reconstruction costs)

themes was then tested with further follow-up interviews and additional expert consultations. This resulted in the refinement of themes where some quotes were recorded, and some were merged into new themes that better reflect the processes governing the design and construction (D&C) of modular adaptable hospitals (See Table 2).

Third, once these themes were recoded and revised, the final set of themes and subthemes, as reflected by the new code structure, was defined, as seen in Table 3. These themes served as the basis for developing the MAHD Evaluation Framework. Hence, the MAHD Framework reflects the importance of the process hierarchy for D&C of modular adaptable hospitals, as reported by the professionals who participated in the interviews and design review sessions.

Following the formulation of the MAHD design guidelines to complement the MAHD evaluation framework and model, these initiatives were then validated through a case study analysis. This case analysis centered on the Island Medical City (IMC) hospital development initiative situated in Penang, Malaysia. IMC acts as a representative case for the MAHD study. Key technical specifics of this project are shown in Table 4.

In the case study analysis, the designs and logistics of the IMC hospital project were thoroughly examined with guidance from the lead architect at Arch'lab. Initially tailored for traditional on-site construction, the existing IMC plans were reshaped to align with the new MAHD systems proposed in this study. This process underscored the critical roles of logistics and technical systems in the MAHD evaluation framework, aiding in fine-tuning the respective subcategories within the framework. The revised concept, encapsulating the adaptations for MAHD compatibility, is illustrated in a series of reconfigured design drawings, showcasing the transformative potential of applying the MAHD principles to the initial plans.

Findings

Overview of Qualitative Coding

Fig. 3 presents the occurrence rate of each theme discussed during the interviews The categories corresponding to the most discussed themes were assigned to a higher level on the MAHD evaluation framework hierarchy, and the ones least mentioned to a lower level. These results are coupled with some of the most representative quotes from interviewed professionals, as outlined in Table 5. These quotes are presented here to provide a more in-depth understanding of the feedback and data collected during the interviews with professionals. These are clustered according to the groups of professionals with the same background and then subdivided to represent their opinions on the strengths, weaknesses, opportunities, and open questions about MAHD.

MAHD Evaluation Framework

The MAHD evaluation framework, as illustrated in Fig. 4, captures the key developmental stages that emerged from interviews with industry experts and design review sessions and the subsequent thematic analysis of the data. The arrangement of framework categories was influenced by insights generated from qualitative interviews. The MAHD evaluation framework outlines a methodical approach to design and construction, encompassing five primary phases, each with four to five subsidiary steps.

First, it is crucial to initiate the process of optimizing digital design. This step entails utilizing digital planning and optimization tools right from the early stages of the design process. It encourages the use of digital simulations to anticipate future demands and operational procedures within healthcare facilities before their initial construction. For instance, when facility owners are in the initial phase of planning the medical services to be offered, it becomes essential to engage in the MAHD zoning activity for these services. The MAHD zoning activity involves identifying the departments and specific areas within them that undergo frequent changes and addressing the need for adaptability. This adaptation can be achieved by incorporating a higher degree of prefabrication for the systems in spaces that require greater flexibility.

Second, it is essential to ensure that project planning and delivery logistics are in sync with the procurement procedures outlined by MAHD. The process of industrialized construction and prefabrication of various systems necessitates careful consideration of off-site manufacturing, system transportation, on-site installation, and compliance with project-specific design and construction regulations, codes, guidelines, and manufacturing constraints. To illustrate, early planning stages need to consider the new hospital's functional spaces and structural grid to accommodate the installation of prefabricated elements and MAHD modules. Similarly, module design and sizing should align with the transportable dimensions specified in local regulations and recommendations.

Third, technical systems include redesign and careful planning to align with the MAHD zoning for functional spaces, considering different levels of adaptability and prefabrication. Furthermore, ensuring that all prefabricated components are furnished with standardized system interfaces is crucial. These interfaces should enable swift and smooth maintenance upgrades and ensure healthcare facilities can adapt over their lifecycles without disrupting regular hospital operations and workflows.

Fourth, assessing the economic viability of the proposed new MAHD hospital designs is necessary. This aspect closely aligns with the "Costs" theme, which emerged as the most frequently discussed topic during the initial round of thematic analysis, with some elements related to the "Time (schedule)" theme integrated. However, subsequent expert reviews of the framework have suggested that it is more appropriate to evaluate the economic feasibility only after reaching the "Phase 3–Project" level of development

Table 3. Refined final set of themes and subthemes

Theme	Sub-themes (codes)	Exemplary quotes
Digital design optimization	Plan for different levels of prefabrication Incorporate flexibility and adaptability of functional spaces Optimize the initial process workflows Plan for change-of-use scenarios Minimize reconstruction disturbances	**Hospital architect #1**: "At the earliest stages of planning new hospitals, it is important to create Functional Connection Diagrams that would indicate which zones need to be connected during the initial use, and that would allow to simulate the potential future scenarios. Then, MAHD systems can be used as a targeted approach where they have the greatest effect." **Architect specialized in hospital process optimization** #1: "Apply the digital simulation and optimization on future MAHD projects to test for exact quantifiable benefits of MAHD system. For example, verify the effectiveness of MAHD to design for dynamic mobilization of patients for quick recovery."
Logistics	Transport of MAHD modules Evaluate process for manufacturing modular hospital facilities Plan for site access (Dis)Assembly of MAHD modules and system	**Group of modular manufacturing experts #5**: "To make transportation economically feasible maximize the value of modules by prefabricating as much elements as possible (i.e. finish the walls, furniture, technology, even curtains on the windows . . .)." **Group of modular manufacturing experts #2**: "Primary technical limitations on module design which are then passed over to the architectural design domain are: 1. Transport limitations; 2. Production line limitations (size of the factory main door, size of the robotic maneuver space, or maneuvering space for human crafted manufacture), 3. Site conditions (urban setting, design limitations imposed on trucks and cranes, etc.)."
Technical systems	Structure and materials Facade options MEP systems Special medical equipment User safety (medical facility safety and protection)	**Group of modular manufacturing experts #7**: "We are currently developing a design for a "universal modular room" which is designed as a robust system capable of satisfying the highest ICU requirements, and then internally flexible for adaptation to different scenarios. This product could well be integrated in the future MAHD technologies." **Group of modular manufacturing experts #8**: "Shipbuilding industry can serve as a perfect example of how to standardize the system interfaces so that prefabricate elements and modules can be (de)installed together on site while technical functionality is not interfering with the user space functionality."
Economic feasibility	Initial capital investment Operative costs Reconstruction costs Lifecycle time and costs saving	**Hospital architect #2**: "The ultimate design problem for MAHD is to determine the trade-offs between the increased initial costs (capital costs of the structure, MEP systems, and base infrastructure robustness) and the lifecycle benefit of maximized space flexibility that provides optimization of processes even after reconstruction." **Hospital architect #3**: "Hospital business model is strongly integrated with the ownership structure and the way hospitals are financed. Therefore, the appropriate financing and business schemes need to be developed to promote the long-term planning processes and ultimately bring the lifecycle benefits of MAHD modular adaptability of hospital facilities."
System sustainability	Economic Sustainability of MAHD Social - quality of MAHD hospital design (soft design aspects) Social - health benefits Environmental benefits of MAHD	**Group of modular manufacturing experts #1**: "MAHD design thinking creates opportunity for forming closed material circles, thus bringing waste reduction through material reuse and recycling. Therefore, if the sustainability benefits of MAHD are properly tested and proven, this also offers potential for promoting MAHD with the private clients who can work with the government and private investors to support MAHD with sustainability loans and other financial incentives." **Hospital architect #4**: "It is important to design "good" hospitals because good space means happy staff in the long-run, and happy staff that smiles is the key to successful healing process of the patient. Therefore, when designing with MAHD systems, always think of the long-lasting effect on social relationships and improved health, with technical systems only coming last to support these social processes at hand."

Table 4. Technical details and project brief for the IMC hospital in Penang, Malaysia (Arch'lab)

Items	Descriptions
Architect	Arch'lab (principal), CG Cheng Architect (local)
Client	Island Hospital, Island Medisuite, and IMC Hospitality (100% private enterprise)
Site/location	Penang, Malaysia–site area 18,200 m^2
Program/capacity	Diagnostics and treatment departments (located in the building base), inpatient care department with 300 bedrooms (located in the building tower)
Floor area	Approximately 34,700 m^2
Year of completion	Anticipated on July 4, 2021
Project brief	The Island Medical City (IMC) is a privately financed medical hub in Penang, Malaysia, catering to the burgeoning medical tourism market. The facility includes a 5-story base for diagnostic and out-patient services and a 7-story tower featuring 300 inpatient rooms of various configurations. The project, aiming to optimize short-term economic gains, leverages the low labor costs in Malaysia to adhere to traditional on-site construction methods, foregoing the use of prefabricated elements. This approach, while cost-effective initially, may impact the hospital's adaptability and life cycle costs adversely. Despite a brief hiatus due to the COVID-19 pandemic, the construction remains on track for completion within the scheduled 34 months.

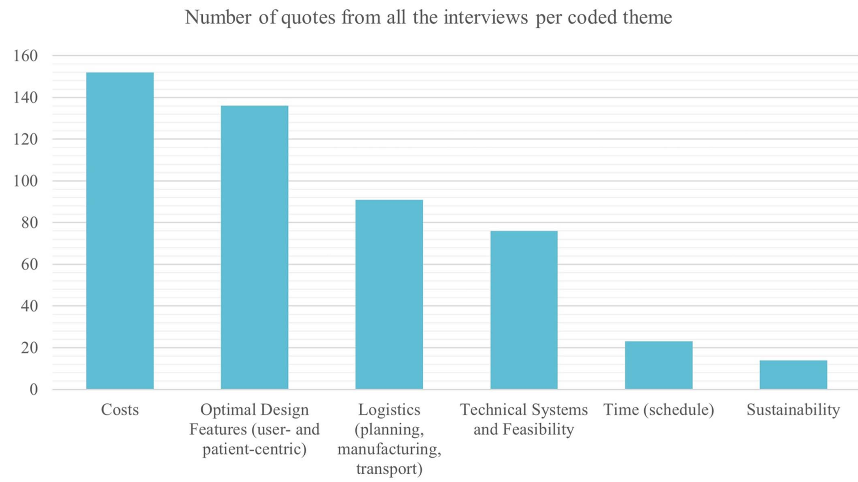

Fig. 3. Number of quotes from all the interviews and design review sessions per coded theme.

in the hospital design process. This level of development is reached only after the selection and design of technical products and systems. Therefore, the assessment of economic feasibility is positioned as the fourth step in the MAHD design process, following the consideration of technical systems.

Fifth, comprehensive consideration should be given to the entire system's sustainability. This involves assessing the new MAHD hospital designs in terms of their ability to maximize economic, social, and environmental sustainability within the MAHD system. This three-pronged approach to evaluating the sustainability of MAHD designs is rooted in the research conducted by Kamali and Hewage (2016, 2017). Previous studies have indicated that implementing industrialized construction methods, such as prefabrication and modular technologies, has the potential to enhance

Table 5. Quotes from interviewed professionals that were coded and thematically analyzed

Interviewees	Themes	Quotes
Module manufacturers	Strengths	*General agreements are that* ***the more value can be fabricated*** *into the module off-site,* ***the more economically feasible*** *it will be to transport and install 3D modules.* ***Lifting the modules*** *and* ***sliding*** *them in is* ***feasible****, and already done, just like numerous other* ***technical system details****. However, some details have not yet been applied in the hospital construction industry and they need to be tested for MAHD.*
	Weaknesses	*Some manufacturers warn* ***against using the superstructure*** *and promote stacking the modules directly on top of each other due to* ***the increased capital cost*** *investments associated with the proposed MAHD system.* *In most cases it is not necessary to use MAHD and completely change modules. Rather, design modules for* ***internal flexibility of individual interior elements****.*
	Opportunities	*Smaller clinics are more specialized and less likely to change their facilities, so* ***focus on larger hospital systems*** *where flexibility is crucial especially for pandemic preparedness.* *Portion of the building done in MAHD can be under* ***leasing agreement (or similar innovative business models)****. Also,* ***reuse modules*** *between different temporary and permanent facilities to maximize financial benefits.*
	Open questions	*Currently* ***up to 30% of hospital could be planned as fully flexible****, but it is crucial to understand the factors* ***which determine the optimal % of MAHD*** *in a hospital and further research the options for a* ***hybrid solution*** *of a MAHD and traditional hospital.* *Need to convince the owners and architects of the benefits, but most primarily* ***show the economic case analysis*** *in favor of MAHD.*
Hospital architects	Strengths	*It is a crucial benefit for MAHD to consider* ***lifecycle approach*** *to the reuse and* ***rapid noninvasive changes of modules*** *in hospital environments.* ***All the elements of MAHD system have been seen in similar applications, but the innovative approach to their combination reveals a great potential for increased flexibility and adaptability of future hospitals.***
	Weaknesses	*Modular construction failed in the past as being* ***expensive*** *due to structural redundancies and* ***aesthetically limiting****, which gives indication of its inherent flaws that remain today.* ***Lifecycle cost analysis*** *is* ***imprecise*** *at the conceptual level, before the MAHD system details are standardized and tested for re-usability and long-term durability.*
	Opportunities	*Apply the MAHD evaluation tool and framework in a* ***case study*** *of a real hospital project* ***currently under planning in Singapore*** *in order to* ***generalize the MAHD design process principles****.* *MAHD Tool could* ***digitally integrate*** *layers of drawings in 2D and 3D with the* ***information for architects****, on spatial requirements,* ***and engineers****, on system requirements.*
	Open questions	*The key is in finding the optimal ways to* ***build flexible adaptable structural frames*** *that can support a variety of modules while* ***maximizing spatial efficiency*** *(in plan and section)* ***and minimizing tolerance errors****.* *At which level of* ***"architectural time spans"*** *for different systems can the design of hospital spaces contribute the most to the* ***user comfort****,* ***operational process functionality****, and* ***healing social interactions****.*

Table 5. (*Continued*.)

Interviewees	Themes	Quotes
Hospital owner representatives	Strengths	MAHD system could offer great benefits to the rapidly changing **day-clinics** where the large frequency of treated patients demands **minimal disruption to the normal operation** of the hospital as it undergoes changes.
		The current trends in medical treatment indicate a decreasing need for in-patient spaces with increase in day-clinics and non-medical use spaces, so MAHD could be used to make the swift change possible.
	Weaknesses	It would be **great to standardize hospital construction** with MAHD system, however the current **public law for the procurement and delivery** of hospital projects in Switzerland is quite a **showstopper** additionally limited by City Planners.
		Depending on different geographical markets, it might be hard to convince investors for increased capital investments since **finances are more readily available for operative costs**.
	Opportunities	**Standardized structural bay size** could allow space for 2 in-patient rooms to convert into 3 out-patient rooms, while MAHD tool would be used to plan and **evaluate the cost optimization** of such potential future conversion scenarios.
		Integrated Project Delivery contracts might incentivize investors to explore MAHD system and the benefits of industrialized construction methods.
	Open questions	Explore using BIM and virtual reality methods (walkthroughs) for **testing the MAHD system in a digital twin format** to unveil economic and technical feasibility limits.
		Show the **cost cases for expanding the hospital spaces** in horizontal and vertical directions, but also **offer internal flexibility** of spaces to connect them functionally into larger zones.
Architects and consultants specialized in hospital process optimization	Strengths	MAHD modular has the potential to allow for **space extensions and adaptations** that will support **optimal integration of robots and technology** into medical workflows, thus maximizing the operational efficiency in a hospital.
		Hospital planning and construction phase usually take from 8-12 years, while the demands, requirements, and technologies can change drastically. MAHD flexible systems could help mitigate these uncertainties and risks.
	Weaknesses	General experience with the hospital owners was that in most cases they **didn't even know how to utilize the added flexibility**.
		Even if the initial simulations show preliminary need for MAHD adaptability, **without proper process and logistical planning, at the lifecycle level, the full 3D flexibility will never be used**.
	Opportunities	**Workflow process optimization** is the primary driver of the economic lifecycle benefits in a hospital. Hence, MAHD modular will succeed only if it considers the processes from the very beginning.
		The **layering of MAHD spaces** in different zones of 2D to full 3D flexibility has the potential to bring operative cost savings if it has been simulated and planned properly in a BIM/Digital model prior to any implementation.
	Open questions	Apply the **digital simulation and optimization** on future MAHD projects to test for exact quantifiable benefits of MAHD system. For example, verify the **effectiveness of MAHD to design for dynamic mobilization of patients** for quick recovery.
		Think in more detail about the potential **scenarios where full MAHD 3D flexibility is needed**. Especially **focus on complex changes** (e.g. ICU to operation room) and all the technical details, cost, timeline for the MAHD module disconnection.

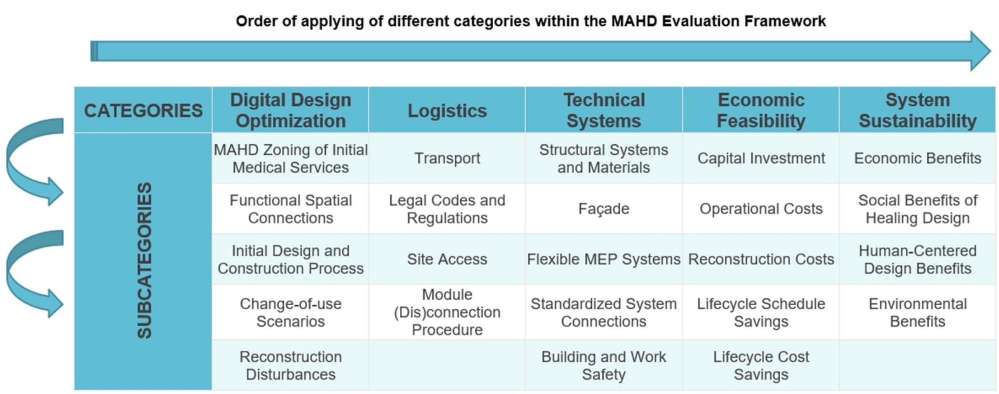

Fig. 4. MAHD evaluation framework.

the overall sustainability of projects, as exemplified within the MAHD framework. However, it is essential to carefully plan and estimate these methods, as emphasized by Kamali and Hewage (2017).

While the individual themes are significant, the endogenous interactions between them are crucial for a holistic implementation. For example, there's a dynamic relationship between economy and sustainability. Cost-effective practices often lead to sustainability, as resource-efficient methods reduce expenses. Conversely, sustainable practices can drive long-term economic benefits through energy savings, reduced waste, and enhanced public image. In addition, digital tools enhance the efficiency of technological implementations in healthcare facilities. For instance, digital simulations can optimize the use of technology in space design, leading to better resource management and adaptability.

MAHD Model

The set of principles encompassed by the MAHD evaluation framework can be illustrated through the MAHD model (see Fig. 5). This

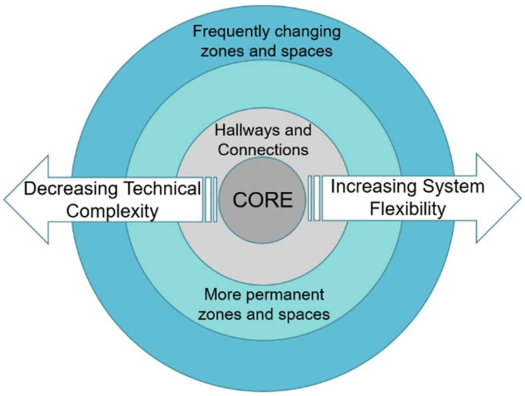

Fig. 5. MAHD model.

model conceptualizes the spatial arrangement of different MAHD zones. Moreover, it presents each zone's technical and procedural specifications within this model.

The primary concept behind this model is to harmonize the requirement for flexibility and adjustability across various hospital departments with the degree of technical maturity offered by different industrialized construction methods. Specifically, the research findings indicate that hospital departments should be arranged in zones of increasing flexibility from the core of the building toward the perimeter, all while being supported by a diminishing level of technical complexity in the systems employed for construction in these zones.

Results also highlight the need to reduce technical complexity in hospital construction systems by distinctly separating components based on their expected lifespan and usage duration in various hospital departments. It advocates for a simplification achieved by utilizing industrialized construction technologies, including prefabricated elements, two-dimensional (2D) panels, and fully furnished three-dimensional (3D) modules. The flexibility and adaptability of departments and individual spaces are evaluated based on the average time it takes for technology and processes to evolve substantially, necessitating a total reconstruction of the facilities. Adaptability needs were analyzed for standard hospital departments as outlined by Rivas and Vilcahuamán (2017) and Neufert (2019). Expert opinions on the optimal level of prefabrication for varying departmental flexibility needs are detailed in Table 6. The table categorizes hospital departments based on the flexibility of their physical structure and their intended use. It outlines a color-coded system that ranges from fully modular, frequently changing rooms to traditional, static structures.

MAHD Guidelines to Implement the Evaluation Framework and Model

The main objective of the MAHD guidelines is to enhance the MAHD evaluation framework and model, as emphasized in a design review session with a hospital architect:

> For architects to comprehend the MAHD design concept, there should be a set of clear drawings and instructions to tell the architects which spatial constraints are imposed on the MAHD design by the logistic and technical systems requirements. Then, the architects can express their aesthetic creativity within this framework that supports the adaptability and flexibility through the MAHD systems.

This study formulated a collection of conceptual design drawing diagrams rooted in the MAHD evaluation framework and model, aiming to foster a wide array of potential design solutions to be incorporated during the design and construction phases. These drawings, showcased in Fig. 6, serve as guidelines, suggesting optimal layouts for healthcare spaces with varying degrees of flexibility and prefabrication in established floor plans. First, the common closed square [see Fig. 6(a)] offers a limited level of modular (only the outer perimeter), but it allows for efficient process flows arranged closely around the core zone. The inner spaces should be planned for extended flexibility by applying prefabricated elements and expandable mechanical systems. Thus, this spatial arrangement is the most suitable for the design of hospital towers with primary uses for inpatient care. Second, if planned with options to access the courtyard logistically, the perforated floor plan layout [see Fig. 6(b)] offers an increased level of modular. The additional design benefits are possible with an emphasis on the courtyard design. Third, the H-shaped floor plan layout [see Fig. 6(c)] offers the maximum level of modular in the enlarged perimeter zones, with additional flexibility ensured in the interior zones using prefabricated components. In addition, Fig. 7 provides a detailed 3D representation of the MAHD system, delineating the superstructure and highlighting the horizontally interchangeable 3D-adaptable MAHD modules which can be inserted into the fixed building infrastructure, accompanied by either integrated or standalone façade components.

Discussions

Implications of MAHD Evaluation Framework

The theoretical justification of the MAHD evaluation framework is based on the work by Salama et al. (2017) and Capolongo et al. (2016). They showed that assessing modular projects early in their

Table 6. MAHD zoning of departments

Color code	Zone level of prefabrication	Departments and specific uses for each zone (based on the MAHD research insights)
Sky blue (dark)	Most frequently changing rooms (fully modular rooms)	Inpatient bedrooms, exam rooms, light therapeutic treatments (day-clinic), surgical treatments (day-clinic)
Sky blue (light)	Less frequently changing rooms (prefabricated elements)	General surgery, diagnostics (heavy duty equipment), administrative services, IT services, storage, toilets
Gray (light)	Hallways and utilities (hybrid = on-site and prefabricated)	Hallways (handicap accessible), building mechanical systems (horizontal HVAC lines), waiting areas, atriums
Gray (dark)	Core and shafts (on-site/traditional method)	Structural, mechanical systems (vertical HVAC shafts), vertical communication, fire escapes

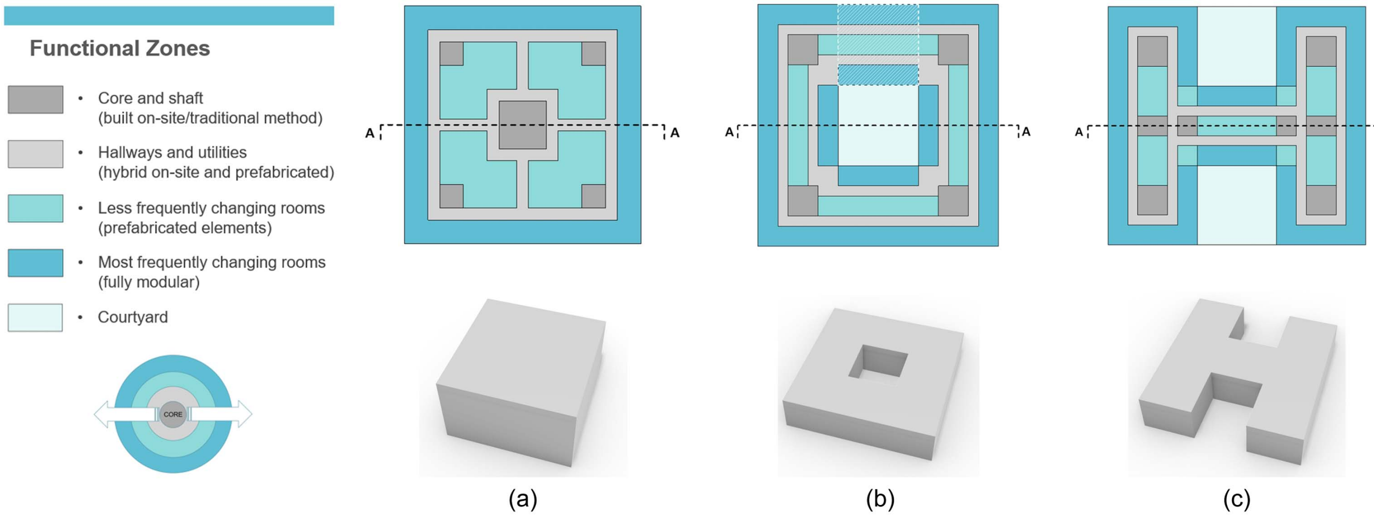

Fig. 6. Examples of conceptual design drawings based on MAHD guidelines.

Fig. 7. MAHD system diagram–with the details of the superstructure and the inserted modules.

design phase using specific criteria can lead to greater savings in time and cost due to the advantages of industrialized construction. In this research, the MAHD evaluation framework is proposed to serve as a starting point to guide future efforts in designing and building hospitals by combining OBC. Existing studies show that although OBC principles have been used in some healthcare facility designs, only appropriate design thinking and organizing can lead to final adaptability and sustainability (Capolongo et al. 2016). This research advances existing research only about healthcare OBC principles to a holistic framework. Thus, it can integrate different OBC parameters together, like the eight parameters proposed by Capolongo et al. (2016) or the hospital adaptable design strategies proposed by Pilosof (2021).

The MAHD evaluation framework focuses on the flexibility and technical aspects of hospital prefabrication levels. This is a direct result of the feedback received during the interviews, where the majority of participants highlighted that not an entire hospital should be built with fully modular and adaptable methods. Instead, the overwhelming professional feedback suggests that different hospital departments should be analyzed for their expected need for flexibility and planned accordingly with a varying degree of system adaptability through the application of technologies with different levels of prefabrication. It reflects the shadow of modular construction on healthcare construction. Healthcare facilities have some very unique and nonstandardized departments, like medical laboratory, operation theater, and diagnostic room (Mills et al. 2020). Modularizing these departments in a single project may be costly and unsustainable. By adopting the idea of MAHD, separating healthcare facilities' systems could be a potential solution to deal with those departments that are not suitable for high-level prefabrication. Designing a new hospital is already complex due to many laws, regulations, and guidelines. On top of that, it is crucial to carefully consider how the chosen level of prefabrication will impact different areas of the hospital over its lifespan.

Implications of the MAHD Model

Previous design guidelines, like Tan et al. (2020) and Bao et al. (2022), only focus on general modular situations rather than the specific needs of healthcare facilities. One of the crucial design goals in hospitals is to provide easily adaptable facilities that can accommodate all the changes in spatial requirements resulting from rapidly changing technologies, medical procedures, economic, and demographic factors in hospitals (Olsson and Hansen 2010). Furthermore, there is overwhelming research and evidence in support of applying modular design and construction technologies in hospitals to increase the much-desired life cycle adaptability of its facilities (Lawson et al. 2014, Wagenaar et al. 2018). However, the relationship between the prefabrication level and the construction's flexibility and quality is not simple and straightforward (Lu et al. 2018). Instead, a research gap has been identified in the field of providing all healthcare construction stakeholders with a method that would incorporate the most appropriate modular and adaptable principles of design and construction at the earliest stages of planning to maximize the related life cycle benefits. Therefore, the MAHD approach was developed for all the hospital stakeholders to understand the procedure of deciding among varying degrees of system prefabrication to provide the most optimal level of flexibility to hospital departments with differing needs for adaptability.

The variety of opinions and expert estimates embedded in the development of the model and the evaluation framework make them more interdisciplinary and suitable for a wider audience of interested stakeholders. Thus, if the model and the evaluation framework presented in this research are in future work implemented into a digital planning tool, such as a hospital digital twin (Han et al. 2023), they have the potential to help the ecosystem integration for faster implementation of MAHD technologies into the market. Parallel with the development of a digital tool, a technical development of the standardized systems and interfaces should be promoted. The final step of the MAHD method and framework includes receiving feedback from professionals (planners, architects, engineers) and users (owners, staff, patients), which makes it interactive and open for constant refinement. This feature might prove to be crucial for promoting the MAHD appeal to all the interested stakeholders since it proves that MAHD is only complementing the existing relationships and building upon them to make them better, as opposed to completely disregarding the incumbent market holders.

Implications of MAHD Guidelines

The proposed MAHD guidelines are a complementary tool to help the architects, planners, and owners conceptually understand the MAHD approach from the earliest stages of project development. The earlier the crucial partners start collaborating and evaluating their design intent against the principles of MAHD, the more likely the greater MAHD's benefits will be exhibited. The concept drawings and the design recommendations in the footnotes reflected the essences of modularity, namely abstraction, information hiding and interface, proposed by Baldwin et al. (2000) and illustrated by Tan et al. (2022) in architectural design. This study provided practical guidelines specifically for the hospital design setting by enriching the academic landscape in the system separation emphasized by Macchi (2018). For example, once a general shape of the building is known, an architect might find it helpful to consult with the concept drawings in the guidelines on how to arrange different MAHD zones across the floor plan and in sections. This will also give information to the technical system manufacturer on the number and size of large vertical shafts in the fixed core of the building and a preliminary understanding of the distribution of the horizontal MEP prefabricated racks. Therefore, the first few steps of the MAHD evaluation framework can be covered in an almost simultaneous process. If coupled with the building information modeling (BIM) technologies and digital planning tool features, this can result in the automated production of preliminary economic feasibility estimates that can help owners evaluate their preferred scenarios. Depending on the design requirements set by the owner, then this iterative process can continue until these requirements are satisfied. Therefore, although these guidelines are presented in a static 2D format, they are envisioned and prepared with the future outlook of being incorporated as part of a digital parametric planning tool that can guide the process of MAHD toward optimal results and construction of better-quality adaptable hospitals.

Conclusions

Healthcare facilities play a pivotal role in realizing universal health coverage and SDGs via the built environment (Li et al. 2021). While transformative construction methods, like industrialized construction, pose challenges to sustainable healthcare design, the COVID-19 pandemic has spotlighted the importance of modular and adaptive approaches (Tan et al. 2021). Yet, a pressing concern remains designing for routine healthcare facilities beyond emergency scenarios. This study introduces an MAHD approach rooted in the OBC for industrialized healthcare construction. It features an evaluation framework with five main design categories and 23 subcategories, accompanied by specific design guidelines. This research does not try to claim that modular construction is a one-size-fits-all solution for most general healthcare construction, but emphasizes that MAHD could be a solution for sustainability.

The MAHD evaluation framework emphasizes the importance of utilizing digital design optimization for healthcare facilities, ensuring design logistics align with MAHD procurement, and reconfiguring technical systems to accommodate MAHD zoning. Economic feasibility and system sustainability, encompassing economic, social, and environmental aspects, are integral to the approach. The framework aims to meld advanced construction methods, like industrialized construction, with the need for modern hospital designs to enhance overall project sustainability. The MAHD model conceptualizes the spatial zoning of hospital departments based on their need for adaptability and the technical complexity of construction methods. It suggests arranging hospital spaces with increasing flexibility from the building's core to its perimeter, supported by decreasingly complex construction technologies. The model emphasizes simplifying construction through different levels of prefabrication, ranging from 2D panels to 3D modules, tailored to the expected lifespan and usage needs of individual hospital spaces. Finally, this research proposes MAHD guidelines aiming to enhance the MAHD evaluation framework and model by introducing conceptual design diagrams that showcase a spectrum of design solutions to be incorporated into the design and construction phases.

Theoretically, the study's introduction of the MAHD approach rooted in the OBC for industrialized healthcare construction significantly enriches the academic landscape in the system separation of healthcare design. This conceptual tool offers a fresh lens through which practitioners can deal with the complexity of healthcare facilities and shapes the theoretical advances around adaptability and modularity. Furthermore, the MAHD model's unique perspective on hospital space zoning, determined by adaptability needs and technical construction complexities, offers a new theoretical dimension, challenging conventional paradigms of spatial design. Most importantly, the research deepens the theoretical breadth by linking modularity theory, traditionally rooted in manufacturing and product design, to the architectural design domain. Doing so emphasizes modularity principles' potential to reshape how we conceptualize, design, and construct modern healthcare facilities.

Regarding practical contribution, in the wake of the COVID-19 pandemic, the pressing need for flexible and adaptive healthcare facilities became evident. This research directly addresses this contemporary challenge by presenting an MAHD approach tailored to these pivotal spaces' industrialized construction. Beyond merely highlighting the importance of such adaptability, the study further equips practitioners with actionable guidelines that serve as a detailed roadmap. This research also has some limitations. The research data were mainly collected from Europe. Healthcare construction is primarily funded and carried out by local governments, making its design closely tied to the local context. Many other countries may have their unique design and construction challenges. However, regarding some more fundamental levels, this research argues that complexity and the methods to solve complexity share some common strategies across different hospital projects, which are decided by the nature of this type of building. The guidelines developed in this research are not a one-size-fits-all solution but rather a recommendation for potential use. Future research could explore the real-world implementation and evaluation of MAHD through longitudinal case studies, its customization across diverse contexts and settings, the integration of cutting-edge technologies for enhanced healthcare efficiency, and its resilience in addressing future global health challenges.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

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