Space resilience and hybrid modular architecture

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Abstract

Objectives: This research explores the potential of Hybrid Modular Architecture (HMA) to improve hospital design and enhance healthcare infrastructure resilience. By integrating prefabricated modular components with site-specific construction, HMA offers a flexible and efficient approach to improving existing hospitals and overall hospital design. The main subject of this paper refers to HMA systems that incorporate smart modules capable of optimizing patient flow and organizing hospital visits by streamlining administrative processes, reducing waiting times, and improving overall patient experience. **Prior work:** This study examines how HMA surpasses its predecessors, the traditional and modular emergency hospitals in construction speed, cost-efficiency, adaptability, sustainability, and resilience by integrating modular design with smart technologies to better respond to emergencies and evolving healthcare needs. **Approach:** This research utilized a mixed-methods approach combining case studies, surveys, and expert interviews to explore the application of HMA in hospitals. Surveys and interviews gathered insights from healthcare professionals and architects on flexibility and scalability. Additionally, literature reviews provided a theoretical foundation to support empirical findings. **Results:** The study revealed that HMA systems can reduce hospital construction time by up to 50% while maintaining quality. Findings from case studies and surveys highlighted increased adaptability, allowing hospitals to reconfigure spaces swiftly to address patient surges. Expert interviews emphasized the benefits of modular partitions and reduced environmental impact. **Implications:** The study provides valuable insights for academics, researchers, and practitioners in architecture and healthcare. For academics, it expands the theoretical understanding of modular design in healthcare contexts. For practitioners, the research highlights practical strategies for enhancing hospital resilience and scalability, particularly in emergencies for future-proofing healthcare facilities. **Value:** This research explores integrating existing hospitals with modular extensions to quickly expand capacity and enhance flexibility. It offers a sustainable, scalable solution for resilient healthcare, bridging theory and practice in architectural design.

Keywords: healthcare infrastructure, patient flow, sustainability, emergency, future-proof

1. Introduction

1.1. Hospital infrastructure issues in Romania

The hospital infrastructure in Romania faces multiple challenges that affect its capacity to provide efficient, safe and modern healthcare services. One of the main problems is the insufficient existing capacity, both in terms of number of beds and geographical distribution of medical facilities, which creates major disparities between urban and rural areas. In addition, many hospitals operate in old buildings with outdated infrastructure, unable to cope with the technological requirements of contemporary medicine or to ensure the necessary safety standards, especially in the context of the frequent seismic risks in the country. This situation is aggravated by chronic underfunding and inefficient resource management, which limits access to advanced medical technologies and innovations, thus putting patients and medical staff in precarious situations. The COVID-19 pandemic has also highlighted the acute vulnerabilities of the system, emphasizing the need for flexible and rapid solutions, such as the integration of modular units, to respond to increasing demands in a short timeframe. In this context, rethinking hospital infrastructure is becoming imperative, adopting hybrid and modular solutions that increase resilience, optimize the use of resources and ensure an adequate response to current and future healthcare demands.

1.2. Context:

In the context of accelerated development and the imperative to modernize the healthcare infrastructure, it becomes crucial to adopt architectural solutions capable of meeting the varied and ever-changing requirements of contemporary hospitals. Hybrid Modular Architecture (HMA) is an approach characterized by increased flexibility and operational efficiency, thus qualifying as a sustainable solution for both the construction, expansion and modification of existing healthcare facilities. [1]

The hybrid hospital, as an expression of this paradigm, encompasses a mixed system that combines the traditional hospital structure with additional smart, prefabricated, add-on modules. These modules not only increase the adaptability and resilience of the space, but also allow for rapid customization of facilities according to the needs of the users, taking into account the specific operational context. In this way, expanding a hospital's capacity becomes an agile and efficient process, thanks to prefabricated modular technologies that ensure speed, minimize disruption and optimize costs. [2]

Fig. 1 – 3D Concept of a Module
Source: Belongs to the Author

1.3. Objective:

The analysis of the implementation process of Hybrid Modular Architecture (HMA) aims to highlight the critical steps of integrating this architectural solution into the infrastructure of an existing hospital. The paper explores how HMA combines the flexibility of modular construction with smart design principles, contributing to the adaptability of the infrastructure and optimizing the functionality of the hospital in relation to the needs of the users.

Also, the integration of smart city concepts and the use of artificial intelligence are analyzed as essential factors in improving the design, construction and operational management processes. These components enable efficient monitoring of resources, reduction of implementation times and the creation of a connected healthcare environment capable of responding rapidly to contemporary challenges. The impact assessment will focus on the efficiency achieved, the adaptability of the solution and its contribution to the development of sustainable and integrated healthcare infrastructures in smart urban ecosystems.

The main objectives of the Hybrid Modular Architecture (HMA) are to increase the flexibility and adaptability of hospital infrastructures, while ensuring rapid and efficient deployment. A significant advantage of the HMA is its increased resilience, due to its modular design that allows for rapid adaptation to future changes and expansions, as well as increased resistance to natural disasters or other disruptions. In terms of sustainability, HMA stands out for its use of eco-friendly materials and reduced construction waste, thanks to its precise and controlled prefabrication process. These features contribute to a reduced environmental impact and a more sustainable and efficient infrastructure in the long term.

- **What is HMA**: Hybrid Modular Architecture (HMA) combines prefabricated modules equipped with inelastic systems and artificial intelligence with traditional building elements, offering design flexibility and construction efficiency in response to needs. Modules for neonatal, modules for UPU, modules for patient distribution, decontamination modules, etc. Modular hybridization is the mixed use of existing elements, a structure or even a building and an addition of modules that aim to extend the building, in order to develop flexibility, and adapt it to the needs of users. In essence, hybridization means changing the typology and technology of the residential building in response to the needs expressed by new user behaviour. In practical terms, this means distinguishing between permanent and temporary typological and technological components in relation to the identified characteristics of the new needs for living in or using the building.
- **Components**: volumetric modules (three-dimensional prefabricated units), smart components (artificial intelligence, computer and installations) and panel components (prefabricated wall, floor and roof elements).

The implementation of Hybrid Modular Architecture (HMA) in hospitals is essential to increase resilience to man-made and natural disasters. The current context, marked by the

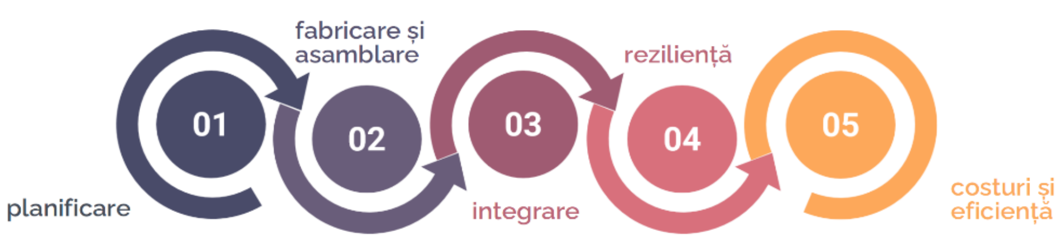

Fig.2 – Graphic
Source: Belongs to the Author

increased frequency of such events, requires medical infrastructures that can be rapidly adapted and expanded to cope with emergencies. [3]The prefabricated modules are designed to withstand earthquakes, floods and other calamities, reducing downtime and ensuring the safety of patients and medical staff. This ability to respond promptly and effectively to disasters is crucial to keep hospitals functional in critical situations.

2. Multihazard response:

A hazard is a potentially harmful physical event, phenomenon and/or human activity, **-** that can cause loss of life or injury, property damage, social and economic harm and environmental degradation Advantages: Hospitals and health facilities often use modular construction for specialized rooms or complete buildings. The main advantage is the installation and testing of medical equipment in a controlled factory. Modular construction expands existing hospitals without affecting patient care, adding wards and various facilities as needed.

2.1. Planning

The process of implementing Hybrid Modular Architecture (HMA) begins with detailed and rigorous planning. This involves assessing the specific needs of the hospital, analyzing the building site, and developing a modular design tailored to the functional and structural requirements. [4]During this phase, project objectives are established, the required module types are selected and transportation and installation logistics are planned. A crucial aspect is the integration of the modules with the hospital's existing infrastructure, which requires close collaboration between architects, engineers and project managers to ensure compatibility and optimal functionality of the new structures.

Fig. 3 – 3D Concept of a Module
Source: Belongs to the Author

2.2. Manufacturing and Assembly

Once the planning is completed, the modules are manufactured in specialized production facilities. Prefabricated manufacturing allows for rigorous quality control and efficient use of materials, ensuring the precision and consistency of each module. Materials are chosen

Fig. 4 – 3D Concept of a Module
Source: Belongs to the Author

for durability and sustainability, contributing to energy efficiency and reducing environmental impact. [1] The prefabricated modules are then transported to the construction site, where the assembly process begins. Rapid sliding and clamping techniques allow the modules to be precisely aligned and fixed to prefabricated foundations. Anchors and connectors are used to ensure structural stability and security, while quick clamping systems facilitate efficient and safe assembly of the modules.

2.3. Integration:

Integration of the prefabricated modules with existing hospital infrastructure is essential to ensure functionality and continuity of operations. Quick and flexible connections allow easy integration of utility systems such as water, electricity and ventilation with existing networks [2] [3]. Flexible connections and modular connectors make it easy to adapt modules to existing structures, minimizing operational disruptions. In addition, aesthetic and functional integration of the new modules is ensured, maintaining consistency with the hospital's design and architecture. Final testing and verification of the systems ensures that all components function properly and that the new structures are ready to meet the needs of patients and medical staff.

3. Extending Hospitals through HMA

Fig. 5 -3D Concept of a Module
Source: Belongs to the Author

a. Foundations:

- Precast Foundations:
  - The use of prefabricated foundations that allow quick and precise installation of the modules.

- The foundations can be adjusted and leveled to ensure stability and perfect alignment of the modules.
- Anchoring Systems:
  - Steel anchors and fasteners are integrated into the foundations to ensure structural stability and to allow for future extensions.

b. Assembling and sliding modules:

- Sliding Technique:
  - Modules are designed to slide on rails or rollers, facilitating precise alignment and reducing assembly time.
  - Using temporary rails to guide the modules into the correct position before fixing.
- Gripping Systems:
  - Modular inter-locking connections that ensure a perfect fit between modules.
  - The use of connectors and quick-clamps to secure modules together, allowing later disassembly and relocation if necessary.

c. Connecting to the existing infrastructure:

- Utilities Integration:
  - Quick connection systems for water, electricity, ventilation and other utilities, ensuring seamless integration with existing infrastructure.
  - Using flexible connections and modular connectors to facilitate easy connection and disconnection.
- Adapting the modules to the existing structure:
  - Modules are configured to match existing buildings using anchor points and adaptable structural frames.

d. Structural Stability:

- Anchoring Modules:
  - The use of chemical and mechanical anchors to secure modules to foundations and ensure stability against lateral forces such as strong winds or earthquakes.
- Stiffening Structures:
  - The integration of stiffening frames into modules to prevent deformation and ensure structural integrity.
  - Use of reinforcing panels and metal reinforcements to increase resistance to seismic forces.

3.1. User Satisfaction:

User satisfaction, including patient and medical staff satisfaction, is a key indicator of successful HMA implementation. The prefabricated modules provide a modern and well-equipped working environment, which contributes to increased morale and productivity of the medical staff. Patients benefit from comfortable and well-equipped treatment spaces that enhance the care experience and overall satisfaction. In addition, the flexibility of the modular design allows spaces to be quickly adapted according to user feedback, ensuring a high level of customization and prompt response to specific needs, ICU modules, complex operating theatre modules, decontamination modules, neonatal modules, UPU modules, patient distribution modules. Thus, the implementation of HMA contributes to a more efficient and satisfying care environment for all users. [5]

3.2. Global Impact Assessment

The global impact assessment of HMA implementation in hospitals shows clear benefits in terms of resilience, cost, efficiency and user satisfaction. Modular construction allows hospitals to adapt quickly to changing demographics and increasing demand for healthcare services, providing a scalable and sustainable solution. Benchmarking shows substantial long-term cost savings due to energy efficiency and durability of materials used. Improving the resilience of healthcare infrastructure also ensures the continuity of critical services under adverse conditions, strengthening the ability of hospitals to face future challenges. [6]

3.3. Conclusions

Implementing Hybrid Modular Architecture in hospitals is a feasible and effective solution for expanding and modernizing healthcare infrastructure. The multiple benefits, ranging from increased resilience and operational efficiency to reduced costs and user satisfaction, demonstrate the added value of HMA in the current context of healthcare challenges.

Fig. 6 – 3D Model Concept of Decontamination Modules
Source: Belongs to the Author

Careful planning, the use of sustainable materials and advanced technologies, as well as the ability to integrate with existing structures, make HMA a strategic choice for hospital infrastructure development. This modular approach not only addresses today's needs, but also prepares hospitals for a more resilient and sustainable future.

4. HMA Concept Examples

Mobile decontamination corridors with hybrid modules are a functional and adaptable architectural solution designed to meet the stringent requirements associated with emergency situations such as chemical, biological, radiological or nuclear (CBRN) incidents. These structures are designed as prefabricated modular elements, easy to transport and assemble, that can be integrated into the infrastructure of a smart city to ensure an efficient and well-coordinated response. The modules include specialized systems such as decontamination showers, advanced filtration units and automatic dispensers for personal protective equipment (PPE), all managed through digital technologies for process optimization. The modular design of the corridors allows for high adaptability to the requirements of the situation. Modules can be interconnected to form corridors of variable sizes, capable of handling flows of contaminated or exposed people, depending on the required capacity. The integration of IoT (Internet of Things) technologies ensures constant monitoring of contamination levels and automatic adjustment of operational parameters, allowing rational use of resources and increased efficiency. The portability of the modules is facilitated by their compact design, making them easy to deploy in close proximity to affected areas, including through the use of smart cities' autonomous transportation networks.

The functionality of the corridors is supported by the integration of complex ventilation and filtration systems that prevent the spread of contaminants into the environment. Water used in the decontamination process is collected, treated and recycled in a sustainable way, reducing the impact on natural resources. The modules are designed to be powered by renewable energy sources, such as solar panels or green generators, allowing them to operate independently from conventional power grids.

Fig. 7 - Concept 3D Modul Tip
Sursă: Aparține Autorului

The decontamination process is organized in clear steps, with each module responsible for a specific function, such as removing contaminated clothing, cleaning with decontaminating solutions, drying and re-equipping. Smart sensors built into the modules analyze contamination levels and adjust process parameters in real time, ensuring compliance with safety protocols. Digital technologies, including augmented reality, can be used to guide staff and affected individuals through the entire process, increasing the efficiency and safety of operations.

The integration of these mobile decontamination corridors into overall urban response plans is facilitated by their connectivity with the digital infrastructure of smart cities. They can communicate directly with command centers and other urban systems, such as hospitals or transport networks, contributing to an efficient coordination of response. In addition, telemedicine terminals integrated into the modules enable remote medical assessment, facilitating patient triage and guiding response teams in real time. Data collected by the modules is analyzed and archived, providing a solid basis for continuous protocol improvement and adaptation to future scenarios.

Through its features, this architectural and technological solution represents an effective integration between the principles of modular architecture and the technological requirements of smart cities. Mobile decontamination corridors contribute to strengthening urban resilience and provide a scalable and sustainable model for crisis management.

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