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Analysing the Modular Design Strategies to Enhance the Adaptive Capacity of Buildings

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ABSTRACT:

In recent years all industries have faced a growing demand for customizable and flexible products that are adaptable to human needs. Buildings being an integral part of our daily lives provide a space to live, work, learn, and socialize and are thus driven to be adaptable according to the dynamic needs of the individuals. New design strategies and technologies are required to make it adaptable without consequences on the economy, ecology, waste generation, and energy consumption. This paper explores the potential application of modular design strategies to address the changing needs and ensure the buildings have enhanced adaptive capacity. To comprehend the nature of these changes and building capacity for adaptation, a thorough analysis of a few chosen case studies based on the type of modular design strategy employed was done. In the cases analyzed, strategies were identified and assessed based on adaptability's key determinants and dimensions. The results of the case studies helped in identifying different modular design strategies that can be employed for different building systems for different purposes to enhance the adaptive capacity of a building. Thus, helping in designing future-proof adaptable structures with a modular approach for a sustainable future.

KEYWORDS: adaptability; adaptable building; adaptive capacity; adaptability determinants; modular design; modules

1. INTRODUCTION

Emerging requirements for housing, employment, health, and transportation, among others, are constantly being met by large-scale scale interventions causing up to 60% of building demolitions to adapt to changing requirements(Canada & By, 2004). Structures are typically created and placed as finished, permanent things, representing a single, predetermined scenario of defined shape, function, and performance. Practical adjustments and conversions are difficult due to the lack of adaptability in early design. In order to meet the demands for global sustainability, it is essential to increase buildings' adaptive capacities (Askar et al., 2021) in response to shifting situations and emerging needs with changes in time, user, environment, and technology during the course of their existence (Milwicz & Pasławski, 2018.). ((Ross et al., 2016)Thus making adaptability as a noteworthy topic, increasingly inspiring and presenting regenerative alternatives to today's sometimes outmoded buildings.

A possible strategy to improve the adaptability of buildings is modular design concepts. Breaking down a structure into separate modules or components allows it to be quickly altered, updated, or expanded in response to changing requirements. Because of its many advantages, such as quicker construction timeframes, cost savings, sustainability, and decreased waste, modular architecture is considered a great enabler of adaptability (Li et al., 2008; Ross et al., 2016; Slaughter, 2001; Webb et al., 2000).

ADAPTABLE BUILDINGS

The terminology "adaptability" in architecture is used by a number of different stakeholders, including clients, businesses, and academics (Gosling et al., 2013). As a result, it has a wide range of meanings, which is shown in the several definitions that have been identified for it (Heidrich et al., 2017). Schmidt III and Austin's definition of adaptable architecture, is “the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing its value through life” (Schmidt & Austin, 2009) and the identified dimensions and degrees of adaptability (Heidrich et al., 2017) are used in this paper to evaluate the efficiency of various modular strategies listed with case example.

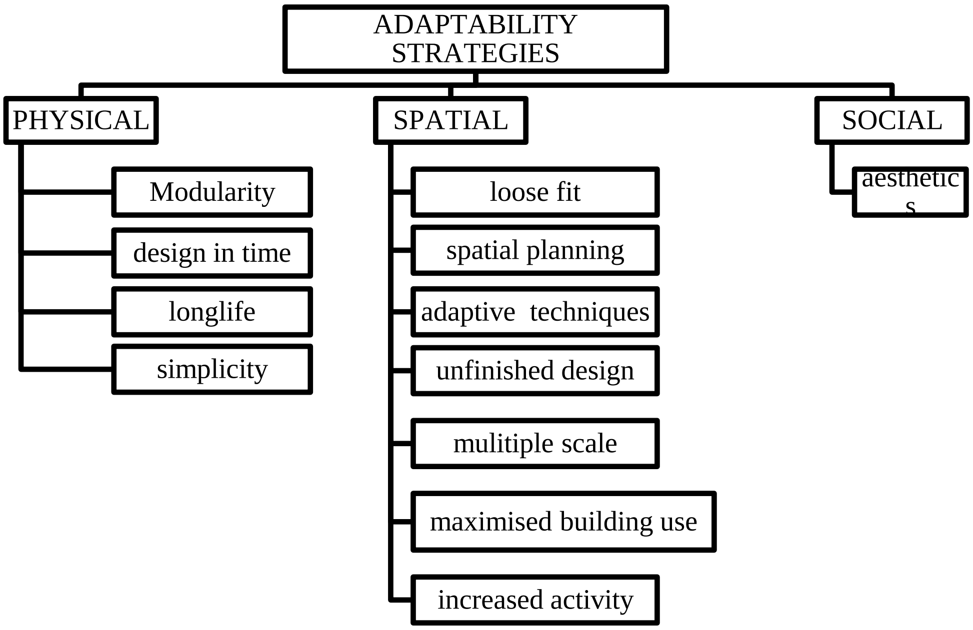

Figure 1 adaptable strategies from literature study (schmidt & austin, 2016)

Buildings' adaptability refers to how easily they can be physically altered, disassembled, renovated, rearranged, repurposed, and/or enlarged. It can be used to encourage sustainability, save the embodied energy, carbon, and prices already incurred in current building materials, as well as aid in preventing pointless demolitions (Ross et al., 2016). Constructing adaptable buildings with a long structural life and a short functional life results in a balanced impact on the environment and the economy (Manewa et al., 2009). The new agenda on sustainability increases the significance of constructing these adaptable buildings. (Kelly et al., 2011) .

3.1. KEY DETERMINANTS AND DIMENSIONS OF ADAPTABILITY:

Adaptive capacity is a tool to assure the building's continued usage. (Geraedts et al., 2014). The main factor influencing it is the changes in building use. Even though change might be unexpected, understanding how structures learn and how they have evolved over time can help us forecast how adaptable they will be. (Kamara et al., 2020). An effective modification is to enhance or fix flaws (or failures) in a system Change (Todnem, 2005) without affecting duration, cost, productivity, and risk distribution (Sun & Meng, 2009). Stewart Brand promotes systems thinking in his book about how buildings learn in response to three drivers: technology, money, and fashion. While doing so, Cost, time, effort, energy, and reusability, are the key determinants that determine the adaptive capacity of a building(van Ellen et al., 2021). Adaptable Futures Research Group, Loughborough University's Robert Schmidt III and associates (schmidt & austin, 2016). Identified: Capacity for change, ability to remain fit for change, productive value cost, and time.(Estaji, 2017) as other key indicators from the literature study. Figure 4 shows the broad determinants of adaptability classified based on the literature.

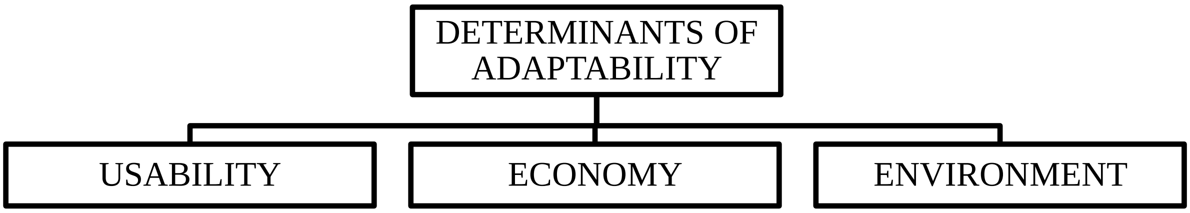

Figure 2 broad determinant categories of adaptability

The literature frequently divides types of adaptability into categories in an effort to describe the changes anticipated; these categories can be related to the type of change (such as spatial layout, building volume, or building use), the speed or magnitude of the change, and whether or not physical alterations are required. Various dimensions of adaptability proposed in the literature are compared and shown in table 1.

Author	**Dimensions**						
(Slaughter, 2001)	Function	capacity	flow				
(Ronn et al., 2012)	Functional	spatial					Aesthetics
Schmidt 2016	adjustable	versatile	refittable	convertible	scalable	movable	
(Geraedts et al., 2014)	organisation	process	product				

Table 1 dimensions of adaptability proposed in literature

4. MODULAR DESIGN

Modular architecture is an approach to designing and constructing buildings, structures, or systems using pre-fabricated, interchangeable components. In order to make a design more effective, versatile, and adaptive to changing needs, it is easier if divided into smaller, self-contained modules that are simple to build and disassemble (Silva & Campos, 2019). A Module is a set of standardized parts or independent units that can be assembled and integrated into a more complex structure. (Silva & Campos, 2019) . A modular structure is a structure made up of independent, functional units (modules) having standardized interfaces and interactions (Kim et al., 2019).

The advantages of modular construction have led to a general acceptance of this approach as being superior to traditional construction methods. When compared to traditional construction methods, it offers a number of benefits, including quicker construction times, less site disruption, cost savings, and flexibility of use ; thus considered one of the key approaches to achieving the key determinants of adaptable architecture (Li et al., 2008; Ross et al., 2016; Schmidt et al., 2011; Slaughter, 2001; Webb et al., 2000).

4.1. MODULAR DESIGN STRATEGIES

Clarifying the kind of relationship, limits, and arrangements of modules is essential for effective future change (Slaughter, 2001). Different type of modules and their characteristics were identified in the literature (Gibb, 2001), distinguished four levels of modularization: components manufacture and subassembly (e.g., doors, light fixtures), non-volumetric preassembly (e.g., panel systems, cladding panels), volumetric preassembly (e.g., plant rooms, bathroom pods), and complete modular buildings (e.g., modular restaurants, multi-family housing). Webb & dagger identified Static modules and Dynamic modules. Beadle identified the Systems module, components, layers and industry process module. This paper broadly classifies the modular design strategy from the literature study. (figure -2)

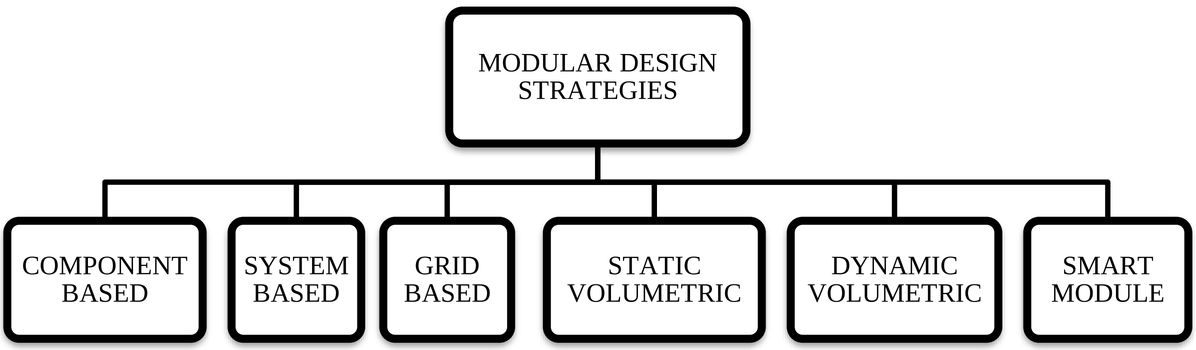

Figure 3 modular design strategies classified from literature

4.1.1. COMPONENT-BASED – MODULARITY

Component-based modularity involves seeing the building as an assembly of individual components (wall component, door component) that could easily be moved, assembled, or disassembled (Gibb, 2001). The building sector has undergone a lot of change thanks to technologies like 3D printing, and prefabrication, becoming more

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agile and adaptable than ever. Building components may be produced precisely with computer-controlled machinery. The manufacture of specialized parts that may be adjusted to particular requirements, has increased the adaptability of building components. Making unique components using conventional manufacturing techniques can be costly and time-consuming. However, it enables the production of structures that would be challenging and can easily be adapted in the individual component level (Gibb, 2001).

Case example: Al Daayan Health District, Qatar

It is a prototype for a low-rise hospital that explores the potential of modularity, and prefabrication with recyclable 3d printed façade components that transforms the aesthetic appearance of the hospital periodically.The idea is a two-story modular building with gardens where patients and workers can relax and take in the natural world. Future facility adaptation will be substantially less expensive because to the modules' ability to be enlarged and altered while causing the least amount of disturbance to care processes. (https://www.e-architect.com/qatar/al-daayan-health-district-masterplan-qatar)

3.1.2. SYSTEM BASED – MODULARITY:

Buildings are not static, monolithic objects, but a series of layers, which change at different rates.(schmidt & austin, 2016) Construction components are separated into layers so they can be maintained or modified without damaging other levels. This intentional strategy minimizes the amount of work to be done, which saves money and time (Gosling et al., 2013) . In order to separate or group the various components with similar functions and characteristics in a building, a hierarchy of architectural layers are used. The difficulty and cost of adaption increase with the number of connectivity between layers (Brand & Stewart, 1994). Various building decomposition systems proposed in the literature are compared and shown in table 1.

AUTHOR	***LAYERS***							
Rush 1986		structure	Envelope	mechanical	interior			
Duffy 1990		Shell		services	scenery	set		
(Slaughter, 2001)		structure	Exterior enclosure	services	Interior finish systems			
Brand 1994	site	structure	Skin	services	Space plan	stuff		

(Schmidt et al., 2011)	surrounding	structure	Skin	services	Space plan	stuff	space	social

Table 2 Various building decompositions systems proposed in the literature

Case example NEXT 21, Japan

NEXT21 was planned such that each of its numerous subsystems could be changed with greater autonomy using a support infill decomposition system to increase the buildings' adaptability. The project's modular systems – A permanent support system with a variable infill system – are made to be easily removable, enabling improvements or repairs to be made without the need for labor-intensive building work. As a result, there is less waste and money spent on construction, and resources are used more sustainably (Sasakura, 2005).

3.1.3. GRID BASED – MODULARITY

A modular grid is a rectangular coordinate reference system where the distance between adjacent lines is the unit. The positions and dimensions of building space components are located using various types of grid patterns: continuous grid, superimposed grid, displacement of the grid (or tartan grids), interrupted grids as neutral zones, and Tartan grids. This system allows for the easy reconfiguration of open spaces which can easily accommodate different types of events and activities ((Sharma et al., 2014).Although it helps with easy expansion it adapts better only with an open building plan.

Case example: IIT Hyderabad

IIT Hyderabad hostel is developed as a system of individual modules with an extendable modular urban structure, which will be used to create accommodation for around 20,000 students over the next 20 years. The grid is composed of four "leaves" modules in a sequence that can be arranged in flexible combinations around a courtyard along a strong pedestrian spine (*GMP - Von Gerkan, Marg Und Partner - Student Housing, IIT Campus, Hyderabad, India | the Plan*, 2018).

STATIC VOLUMETRIC MODULES:

This strategy consists of Static non movable but grid-based volumetric modules that are easily assembled on-site. Prefabrication plays a major role in creating such 3d modules(Webb et al., 2000)

Case example: Shizuoka Press and Broadcasting Center, Tokyo

Tange was inspired by the site's restricted 189 square metre triangular shape to create a vertical structure made up of a primary infrastructure core that could grow into an urban megastructure (a term coined by fellow Metabolist Japanese architect Fumihiko Maki) into which an increasing number of prefabricated capsules could be "plugged-in" (Merin , 2021)

3.1.4. DYNAMIC VOLUMETRIC MODULES

This strategy consists of modules that may be connected to the central core and replaced, moved, or exchanged as needed, it serves as a model for sustainable and recyclable architecture. The metabolism movement played a major role in the creation of such modules. (Webb et al., 2000)

Case example: Nakagin Capsule Tower,Tokyo

A total of 140 capsules are stacked and rotated at various angles around a central core standing 14 stories high. Kurokawa's invention made it possible to attach each unit to the concrete core using only 4 high-tension bolts, maintaining the units' replacement ability. Each capsule is 4 x 2.5 meters in size, giving one person a comfortable place to reside. Each module's interior space can be changed by attaching the capsule to additional capsules.

3.1.5. SMART MODULES:

Artificial intelligence (AI) has the potential to revolutionize the construction sector by making it possible to design flexible, smart building components. Using AI, it is feasible to create building elements that are more adaptive and responsive to changing needs by sensing and reacting to changes in their surroundings. Prieto (2023)

Case example: BetaPort

BETAPORT is a robotic construction system powered by artificial intelligence and automation that employs machine learning and custom algorithms to produce interactive and predictive solutions for effective spatial layouts, logistic flows, and operations with a fully automated feedback mechanism.

4. MODULARITY AND ADAPTABLE BUILDINGS:

Modularity is found to be the most common strategy that relates to the majority of design tactics for achieving adaptability from previous literature (schmidt & austin, 2016) . Modularity is an efficient approach toward adaptable architecture with functional units or modules that can be assembled, reconfigured, modified, and later disassembled. Through the provision of a flexible framework that can be quickly updated or expanded as needed, modularity can improve adaptability in design. Architects can design structures that are simple to modify or add to by employing standardized modules, making it simpler to adapt to shifting needs and circumstances. It also promotes a circular economy with reuse of materials without essential losses (Askar et al., 2021)

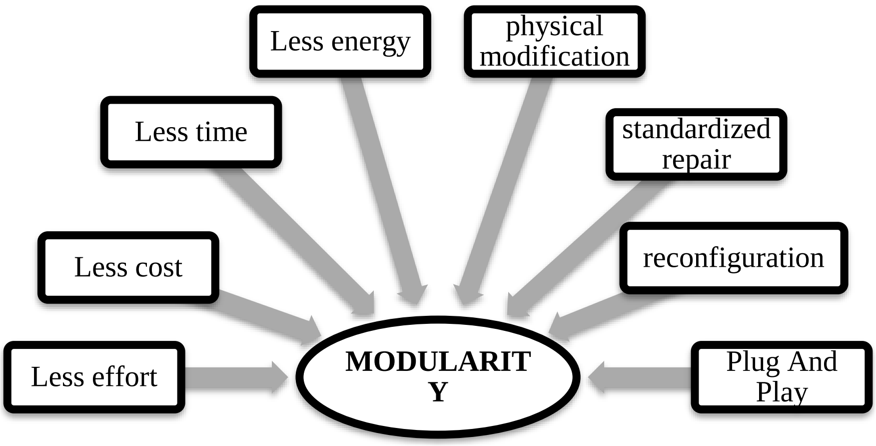

Figure 4 Modularity with major requirements for adaptability

5. CASE STUDY FINDINGS:

The case studies with different modular design strategies are assessed based on the key determinants and dimensions of adaptability. (Table 3) A design strategy gives the architect a way to conceptualize the adaptable structure. The results of the case studies were utilized to demonstrate which strategies will improve the design of adaptive structures Since adaptability is one of many interrelated design issues, the design solutions discussed here are not restricted to designing for adaptation. In order to create a generic building model, all possible design combinations are sought after (Schmidt & Austin, 2009). Each modular design strategy is found to serve a different purpose. The key determinants of adaptability and dimensions of adaptability can be used to determine the type of modular design strategy that is going to be implemented in different elements of building design to create an integrated system with a separate strategy for each building system.

ADAPTABILITY DETERMINANTS		SYSTEM BASED	COMPONENT BASED	GRID BASED	SMART MODULE	STATIC VOLUMTERIC	DYNAMIC VOLUMTERIC
EXAMPLE CASE STUDY		**NEXT 21**	**HEALTH DISTRICT**	**IIT Hyderabad**	**BETAPORT**	**SHIZUOKO CENTRE**	**CAPSULE TOWER**
USABILITY POTENTIAL	Adjustable Task	Non fixed furniture	-	-	Plug and play	Non fixed furniture	-
	Versatile Space (flow flexibility)	Avenues in central courtyard	Perimeter circulation	Point of intersection circulation	Computational algorithm	Centralised circulation	Centralised circulation
	Refittable performance	Separate Skeleton - infill	Prefab modules	Prefab modules	Automated modules	Plug in capsules	Plug in capsules
	Convertible function	reconfigurable infill , flexible service	-	Multifunctional large spaces	Loose fit planning	Open plan movable partitions	-
	Scalable	Divide , add	modules	modules	modules	capsules	capsules
ECONOMY	Cost	Sustainable reusable	3d printed expansion (30% less cost,95% less time)	Prefab expansion (18% less cost,30% less time)	Material , reusable	Prefab Expansion (18% less cost,30% less time)	Modular reusable (20% less cost,50% less time)
	Effort-time	1 year			robot		
ENVIRONMENT		sustainable	nature	facade	material	-	-

Table 3 case study observation

Limitations of the Study: The key limitation of the study is user live feedback and live evaluation of adaptive capacity could not be considered since all the case studies were evaluated with secondary data from the literature.

7. CONCLUSION:

The results of the case studies helped in identifying different modular design strategies for different building systems to enhance the adaptive capacity of a building. Thus helping in designing future-proof adaptable structures with a modular approach for a sustainable future. The rapidly changing needs of society, the advancements in technology, and the growing desire for sustainability are just a few of the driving factors behind the need for adaptable buildings. With the help of integrated modularity in all levels, buildings can be designed to be easily adapted and reconfigured, making them much more efficient and cost-effective in the long run. This approach enables the building to evolve over various spans of time, thereby ensuring that it remains relevant and useful for future generations. This highlighted the significance of including design-level adaptation solutions in future projects that offer sustainable solutions on the levels of the economy, society, and environment. By embracing this approach, architects, engineers, and builders can help ensure that buildings are designed to be not just functional but also responsive to the changing needs of society.

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