Framework for designing adaptable buildings through modularity and DfMA, using digital design and digital fabrication

by

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Cadre conceptuel pour la conception de bâtiments adaptables grâce à la modularité et à la DfMA, en utilisant la conception et la fabrication numériques

Salma OMRANI

RÉSUMÉ

Dans le paysage en constante évolution de l'industrie de la construction, marqué par des avancées technologiques rapides, des contraintes de ressources et des préoccupations environnementales croissantes, la conception de bâtiments adaptables devient de plus en plus critique. Ces conceptions flexibles ont le potentiel de répondre à certains des défis les plus pressants du secteur en intégrant les principes de la Conception pour la Fabrication et l'Assemblage (DfMA) avec les technologies de conception et de fabrication numériques. Cette intégration transparente comble l'écart entre la conception théorique et la mise en œuvre pratique, prête à initier une transformation profonde au sein de l'industrie. Cette recherche introduit un cadre conceptuel intégré, basé sur la modularité et les principes de conception numérique, visant à identifier les éléments et artefacts pivots qui facilitent la construction de bâtiments adaptables. Grâce à ce cadre innovant, un niveau accru de flexibilité et d'adaptativité peut être atteint, grâce à une standardisation facilitée par les techniques de fabrication numérique.

Au-delà de l'exploration théorique, cette thèse basée sur des articles, utilise la méthodologie Design Science Research (DSR) et offre des études de cas pratiques, servant de preuves de la mise en œuvre réussie de la modularité, de la conception numérique et de la fabrication d'artefacts contribuant à l'adaptabilité des bâtiments. Ces projets démontrent des avantages tels qu'une réduction des délais de construction, une minimisation des déchets matériels et une amélioration de l'efficacité globale du projet. Cette recherche compile des preuves concrètes des avantages significatifs et du potentiel transformateur inhérents à l'adoption de la modularité et de la fabrication numérique dans les pratiques de construction. Elle a le potentiel de contribuer à un avenir plus résilient et durable pour l'industrie de la construction. Il ne s'agit pas simplement d'un exercice académique mais d'une contribution au débat en cours sur les pratiques de construction durables et leur intégration pratique. La synthèse de la modularité, de la DfMA et de la fabrication numérique trace une voie évolutive pour le secteur de la construction, promettant des bâtiments qui répondent à des défis multifacettes. En promouvant la durabilité, l'efficacité des ressources et la résilience tout au long du cycle de vie du bâtiment, ces pratiques transformatrices fournissent un chemin vers la circularité dans la construction. Cette recherche a le potentiel de servir de catalyseur de changement en encourageant les architectes, ingénieurs et parties prenantes à adopter des méthodologies de conception innovantes qui entraînent un changement significatif. En fin de compte, elle vise à créer un environnement construit plus conscient de l'environnement.

Mots-clés : DfMA, modularité, fabrication numérique, conception numérique, circularité, adaptabilité

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ABSTRACT

Adaptive building design are becoming increasingly critical in the ever-evolving construction industry landscape, marked by rapid technological advancements, resource constraints, and escalating environmental concerns. These flexible designs hold the potential to address some of the sector's most pressing challenges by integrating Design for Manufacture and Assembly (DfMA) principles with digital design and fabrication technologies, with digital design and manufacturing technologies. This seamless integration bridges the gap between conceptual design and practical implementation, poised to initiate a profound transformation within the industry. This study introduces a comprehensive, integrated conceptual framework grounded in modularity and digital design principles. It aims to identify pivotal elements and artifacts that facilitate adaptable building construction. Through this innovative framework, a heightened level of flexibility and ease of positioning is achieved, which is made possible by the standardization facilitated by digital fabrication techniques.

Beyond theoretical exploration, this article-based thesis uses Design Science Reasearch and offers a collection of case studies and practical illustrations, serving as evidence of the successful implementation of modularity, digital design, and fabrication across diverse construction endeavours. These projects demonstrate substantial advantages, leading to reduced construction timelines, material waste minimization, and improved overall project efficiency. This research compiles concrete evidence of the benefits and transformative potential inherent in adopting modularity and digital fabrication within construction practices. It has the potential to actively shapes a more resilient and sustainable future for the construction industry. This is not merely an academic exercise but a contribution to the ongoing discourse on sustainable construction practices and their practical integration. The synthesis of modularity, DfMA, and digital fabrication charts an evolutionary course for the construction sector, promising buildings that respond to multifaceted challenges. These transformative practices provide a pathway toward a more sustainable future by championing sustainability, resource efficiency, and resilience throughout the building lifecycle. This research can encourage architects, engineers, and stakeholders to embrace innovative design methodologies that drive meaningful change. Ultimately, it seeks to create a more environmentally conscious, adaptable built environment. This will embody the industry's commitment to navigating the evolving landscape while steering towards a sustainable and resilient future.

Keywords: DfMA, modularity, digital fabrication, digital design, circularity, adaptability

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LIST OF ABREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
3DCP	3D Concrete Printing
AM	Additive Manufacturing
BIM	Building Information Modeling
CE	Circular Economy
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CD	Computational Design
CNC	Computer Numerical Control
DfAd	Design for Adaptability
Dfab	Digital Fabrication
DD	Digital Design
DfM	Design for Manufacturing
DfD	Design for Deconstruction
DfMA	Design for Manufacturing and Assembly
DfA	Design for Assembly
DfX	Design for Excellence
GD	Generative Design

INTRODUCTION

The construction of buildings has a profound impact on the environment in terms of the consumption of resources, the use of energy, and the generation of waste. Several traditional construction practices do not adequately address the pressing issues of resource efficiency, sustainability, and adaptability. Numerous challenges must be addressed, including safety hazards, high costs, suboptimal environmental conditions, and compromised quality. Architecture and designers fundamentally influence ecosystems, economies, societies, and cultures. It is estimated that users spend 87% of human life in buildings, the construction industry consumes approximately 40% of the world's resources and energy, the housing population is rising, and contractors can construct 2.6 billion additional urban buildings by 2050 (Schwieger, 2019). A circular economy (CE) is an innovative approach to increase sustainability. To preserve a positive and natural relationship with its surroundings and climate and to sustain its ecology, sustainable architecture focuses on reducing energy and resource consumption, protecting the environment, and enhancing the quality of life of people (Julistiono et al., 2017). Additionally, in the context of construction and architecture, According to Askar et al., 2021, Adaptable buildings contribute to reducing waste materials and energy consumption to minimize the environmental impact of construction.

Furthermore, the design for adaptability (DfAd) is an enabler for achieving CE and could address the issues of "obsolescence" and "redundancy" in a building. As a result of design for adaptability, the lifespan of the building increases through the strategy of adaptability. Adaptable buildings can change and adjust to changing circumstances Nakib, 2010. Generally, CE and DfAd have corporations in "design for long-lasting and durability, design for disassembly and deconstruction (DfD), standardization and modular design" as joint strategies to achieve sustainable construction (Askar et al., 2021). Using Design Science Research (DSR) methodology, this study reviews relevant literature, uses data collection and analysis methods, and implements the conceptual framework using business process mapping notation (BPMN) processes. The thesis synthesizes key findings, provides a comprehensive discussion, and provides valuable insight into future research directions. This thesis represents a significant step forward in adaptable, sustainable, and environmentally responsible building practices. The thesis emphasizes digital design and fabrication's critical role in reshaping the future of construction. It bridges the gap between traditional construction practices and circular economy demands. This research contributes to transforming construction practices for a more sustainable and adaptable environment. It ensures that structures are not static entities but dynamic and versatile spaces. This thesis presents a pioneering approach to transitioning from traditional construction practices to modular construction solutions. It emphasizes the attainment of technological interoperability between digital design and digital fabrication methods, all within a modularity framework. Figure 0.1 illustrates how this study began. This approach uses modularity to allow structure flexibility, enabling them to be easily reconfigured and repurposed in response to changing requirements and needs. In addition to maximizing resource efficiency and minimizing waste, this enhances the longevity of the built environment.

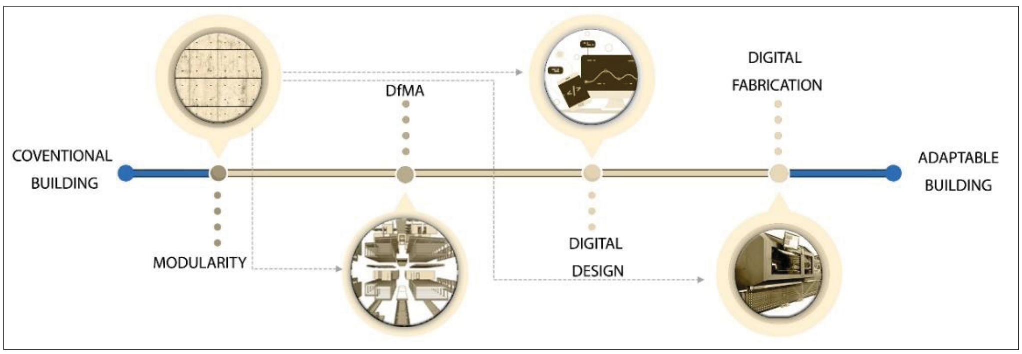


Figure 0.1 An overview of the research project's context

Also, Figure 0.1 illustrates how building methodologies have evolved from traditional to highly adaptable. The design incorporates modern technology and design principles, showing how each component is interconnected. Contemporary building methodologies incorporate advanced materials and technology, making construction more flexible and adaptable. In contrast, traditional methods rely on conventional techniques and materials, which may restrict the possibilities for customization and innovation. Also, modular construction improves quality control, reduces waste, and speeds up construction by manufacturing building components in a controlled factory environment. The principles of DfMA (Design for Manufacture and Assembly) are closely related to those of modular components due to modularity. The building process can be streamlined and cost-effective by designing modules to facilitate easy manufacturing and assembly. DfMA simplifies on-site construction and assembly, leading to faster construction times and lower construction costs. It is possible to create detailed models of buildings and their components using digital design with the aim of manufacturing. Therefore, the transition from design to production is seamless. The building components can be manufactured by using digital fabrication tools such as CNC machines, 3D printers, and robotic assemblers. These tools use digital designs to generate physical objects. By adding, removing, or reconfiguring modules, it is possible to change the size, layout, or function of a building. In addition to extending the lifecycle of the building, adaptability allows it to adapt to future requirements without requiring a complete redevelopment. The following research question has initiated this research:

- Q1: How can integrating modularity, digital design, and digital fabrication within the Design for Adaptability framework contribute to sustainability, circularity and adaptability in building construction?

Three papers, one journal article, and two conference proceedings are included in the thesis as appendices to the last chapter. As a result, this thesis follows these steps (Figure 0.2):

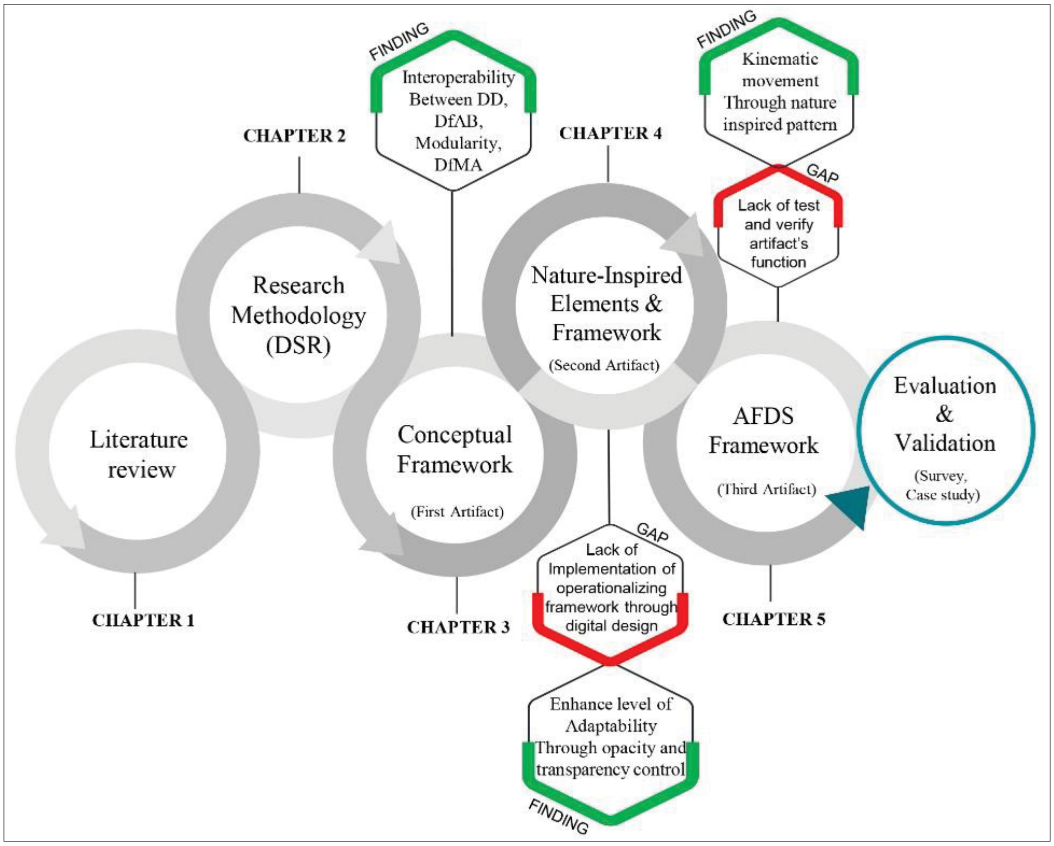


Figure 0.2 The structure of the article-based thesis

This image shows a flowchart that illustrates the structure and progression of a research thesis or dissertation, broken down into chapters and critical components. The parts and their potential interconnections are as follows:

- Chapter 1: Systematic literature review: The first chapter establishes the basis for the research question by reviewing existing literature, identifying gaps, and evaluating current knowledge.
- Chapter 2: Research Methodologies: As a follow-up to the literature review, the second chapter discusses the Design Science Research methodology employed in this study. The DSR methodology includes information systems and technology fields, where artifacts to solve practical problems are created and evaluated.
- Chapter 3: In this chapter, the Conceptual Framework (CF) is introduced in its initial stage. This first version of the CF provides a structured approach to understanding the problem and the various factors that may influence it, laying the groundwork for subsequent research. This chapter

highlights the critical role of seamless integration and coordination between Digital Design (DD), Digital Fabrication (DfAB), Modularity, and Design for Manufacture and Assembly (DfMA) to achieve optimal outcomes.

- Chapter 4: CF implementation using Nature-Inspired Elements: The fourth chapter discusses and relates specific nature-inspired elements to the CF. In this implementation of the CF, adaptability is achieved through a balance of opacity and transparency, depending on user's needs and requirements. The design incorporates elements that can shift between different levels of opacity and transparency. This allows the environment to adapt based on the user's needs, such as privacy, lighting, and aesthetic preferences.
- Chapter 5: In this section, the complete CF is presented together with one of its practical implementations focusing on Modularity and Digital Fabrication as central concepts. This involved the development of detailed engineering prototype. Nature-inspired patterns are integrated to enhance kinematic movement, as testing and verifying the artifact functionality are essential components of the process. Research findings are evaluated using methods such as surveys and case studies, emphasizing an iterative approach that informs every stage from initial requirements to final production revolutionizing the design of interior spaces and facades.

- The conceptual framework is introduced as an artifact (in the sense of the DSR methodology), illustrating the need for interoperability among various techniques like digital design, digital fabrication, modularity, and design for manufacture and assembly. The framework is further developed by incorporating nature-inspired elements, enhancing adaptability and transparency in systems and processes. Practical aspects are addressed with detailed engineering plans, prototypes, and digital mock-ups, highlighting the importance of testing and validating the functionality of artifacts. The iterative nature of the research process is emphasized, with findings from each chapter feeding into the next and allowing for continuous refinement. This comprehensive approach aims to revolutionize the design and construction of interior spaces and facades, ensuring all stages, from initial requirements to final production, are thoroughly integrated and optimized. This research framework demonstrates how integrating digital design, modularity, and nature-inspired elements enhances adaptability in educational buildings, ensuring seamless functionality and innovative spaces.

CHAPTER 1

LITERATURE REVIEW

In this chapter, a literature review was carried out to assess the current research landscape, identify major challenges, and explore future opportunities in the relevant field. A systematic analysis recognizes the modularity concept for producing an adaptable building. Furthermore, the backward and forward snowballing processes facilitate this analysis to identify relevant keywords and domain-related articles. The systematic literature review process involves recognizing and assessing relevant articles on specific issues and the scope of research (Kitchenham, 2004). In addition, in the Cochrane Collaboration, 2014 cited in (Siddaway et al. 2019), there are several advantages to undergoing a systematic review, such as having an in-depth analysis of a defined issue. SLR employs systematic methods to gather information from the relevant articles and resources. To generate maps using network information. VOSviewer software is a tool that represents data and helps researchers understand the scope of research. Van Eck & Waltman, 2010 cited in (Cobo et al. 2012), defined Vosviewer as a software tool used in science visualization with an approximation of subjects. In this report, in the SLR methodology, these items are considered:

- Scopus as the search database.
- Search within the article title, abstract, and keywords.
- Search keywords: “Adaptability and Flexibility” OR “Modularity” OR “Digital Design.”
- Publications published between 2000 and 2021.
- Document type: articles and conference papers.
- Publication language: English.

Figure 1.1 illustrates the authors' co-occurring keywords related to the relevant articles. This Figure contains more occurrences of keywords by applying a picture network map. Based on the publication dates from 2000 to 2022, the relevant research about modularity and adaptability in construction indicates the Vosviewr map. Conducting such analyses is meant to facilitate integration between these themes. In this bibliometric visualization, modularity, robotics, and adaptability are significant nodes with other connections such as life cycle, manufacturing, and computer simulation. In addition, an adaptive system is another concept in this scope.

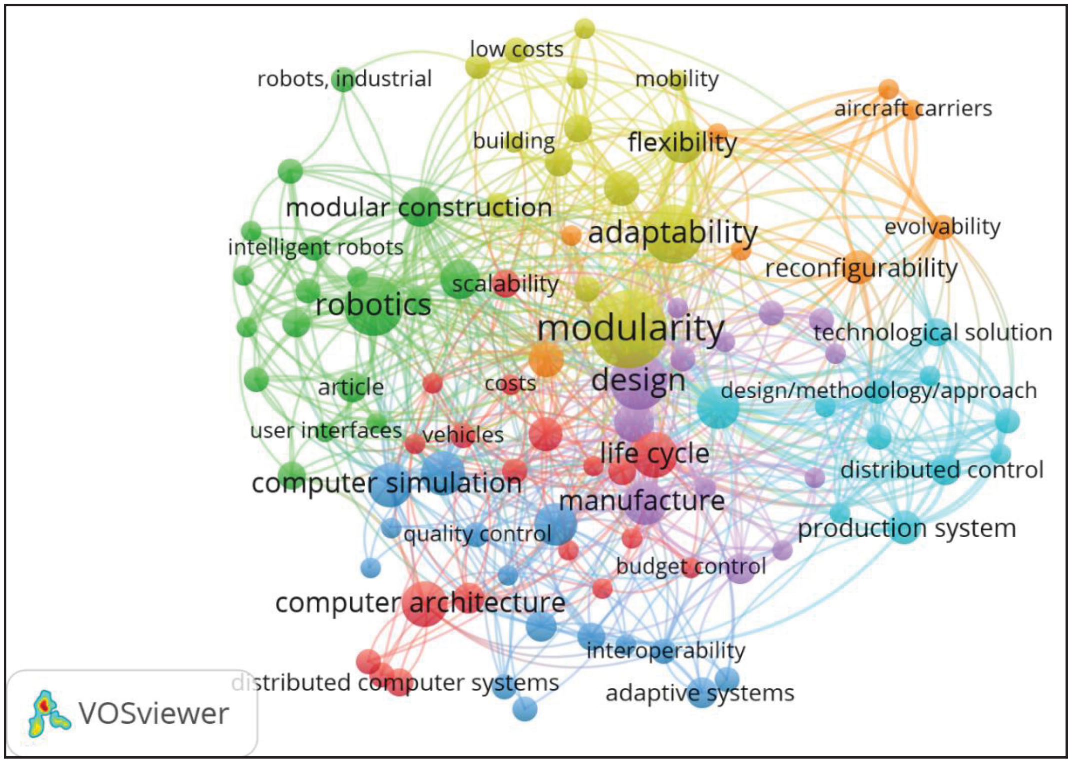


Figure 1.1 Co-occurrence of authors' keywords in the literature review

According to this figure, the keywords "modularity, robots, adaptability, life cycle, computer simulation, modular construction flexibility, design, and control quality" are the most common. Figure 1.2 indicates themes of adaptability and robotics studies: the green cluster involved flexibility, modularity, architectural design, cost, and manufacturing. The blue cluster involved robotics investigating the association between modularity and adaptability within computer-aided design in the construction industry. Figure 1.2 demonstrates the network map of the trend topics according to the keywords used from 2006 to 2014.

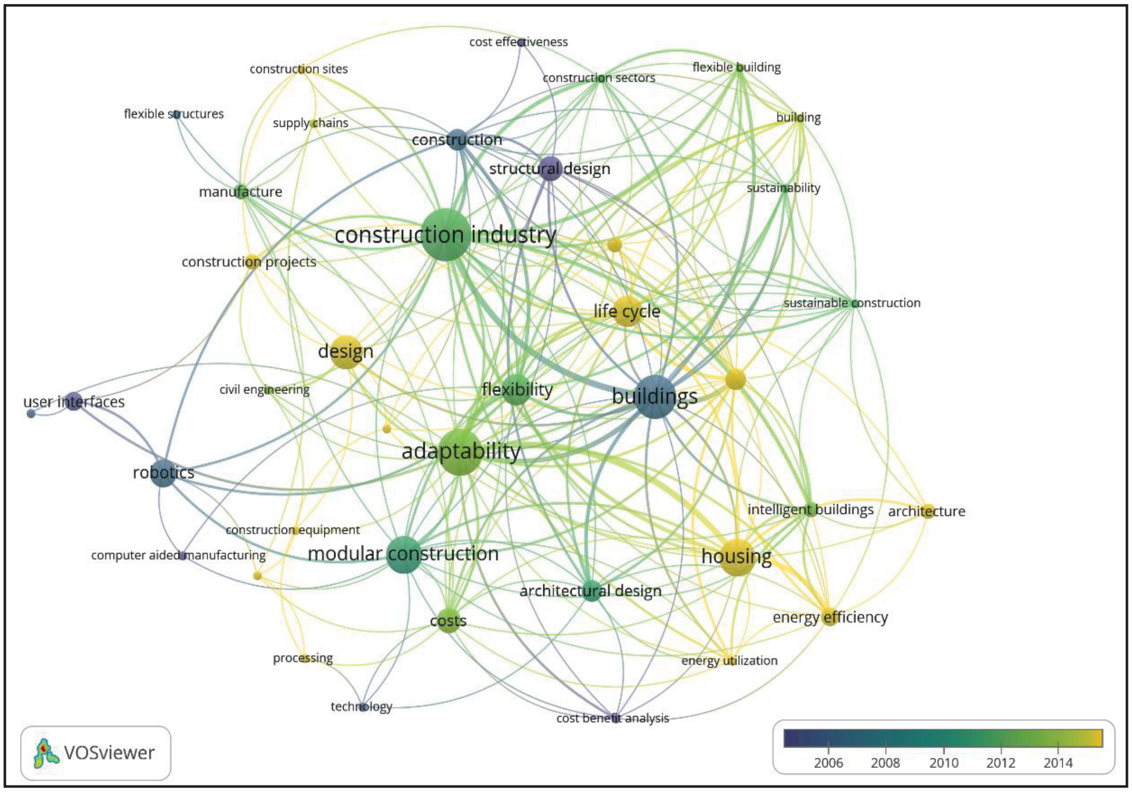


Figure 1.2 Citation of adaptability and modular construction

1.1 Adaptability and flexibility

Due to complexity, uncertainty, rapid technological advancements, and functional obsolescence, today's building systems design is challenging. A flexible system can easily be modified and adapted to changes in the environment conveniently and promptly. DfAd can solve obsolescence and redundancy problems (Cristiana Cellucci & Michele Di Sivo, 2015). The following table 1.1, indicates the definitions of adaptability and flexibility.

Table 1.1 Definition of adaptability

Authors	Years	Definition of Adaptability
Austin (2007) cited in Ismail and Rahim	2011	"Able to respond effectively to changing household needs without requiring costly and energy-intensive alterations."
Haber fellner, R. et al. 2005 cited in Askar et al.	2021	"The ability of a system to change internally and autonomously to follow changes in its environment."
oss BE, C et al., 2016 cited in (McFarland et al.,)	2021	"The ease with which a building can be physically modified, deconstructed, refurbished, reconfigured, repurposed and expanded."
Ismail, Z.; Rahim 2011 cited in Askar et al.	2021	"Adaptable architecture is "an architecture from which specific components can be changed in response to external stimuli, for example, the users or environment."
Authors	Years	Definition of Flexibility
Altan. H. et al., 2015 cited in Kasra Mirpadyab et al.,	2020	"The term flexible architecture describes an architecture from which specific features can be changed in response to external affection, for instance, the users or environment. This change occurs by the building system, turned manually into or could be any other ability to transform by an external force".
UNEP (United Nations Environment Programme). 2005. Cited in (Cristiana Cellucci & Michele Di Sivo,)	2015	"Flexibility makes the system resilient and capable of absorbing shocks and environmental disturbances without undergoing major alterations in its functional organization, structure or identifying characteristics."

By adapting the spatial layout and interior spaces, flexibility assists in making a versatile and internal conversion in the building. In addition, there are four major approaches to having flexibility in the structure (Cristiana Cellucci & Michele Di Sivo, 2015):

- "Spatial flexibility in fixed surface area"
- "Evolutionary spatial flexibility"
- "Technological flexibility related to construction techniques"
- "Technological flexibility related to the easy maintenance of the installations and building sub-systems"

Also, there are different terms for adaptation (Ismail and Rahim 2011).

- Flexibility refers to adapting to changes due to the user's needs. As defined by this term, the user may modify components by using machine-driven or automatic techniques. (Leupen 2002).
- Active: Using this term, the components can adapt to external changes, such as environmental changes, through user interaction. There is a need for electrical techniques. (Giddens, 1990).
- Dynamic: In this case, one system could be defined with one input to answer different changes. Computer aid is required in this part (Rutten & Trum, 2000).
- Interactive: Refers to integrating the user's needs with the system's potential to respond to the changes. Digital sensors and programming are essential in this context (Von Stamm, 2003).
- Intelligent: Components can be modified and adapted to these changes using system control. A computer program controls an intelligent system. A system control allows the components to be monitored and adjusted as users' need, while the computer program provides the intelligence necessary to make the changes. This combination of components allows the system to be easily modified and adapted to changing conditions (Van Mele, 2003).
- Smart: As the name implies, this refers to the ability of components of a building to be modified independently. The system has a feature known as "self-initiative". The system can comprehend the changes and plan a strategy for adapting (Vincent, 2001).

Furthermore, other terms are associated with adaptability, such as "transformability, changeability, flexibility, elasticity, commonality, modularity, standardization, convertibility, and upgradeability" (Askar et al., 2021).

1.1.1 Level of adaptability and flexibility

The concept of building adaptability or flexibility refers to the ability of a building to meet changing needs and functions over time, often referred to as "building adaptability" or "building flexibility." Adaptable and flexible buildings can be repurposed, expanded, or modified without requiring significant structural or architectural changes. The building has distinct levels of adaptability and flexibility (Nakib, 2010).

- Individual level: By adapting, users can achieve their requirements, comfort, security, and quality, as well as enhance their connection with the building and other users.
- Socially: People rely on adaptability to fulfill their social and individual needs, allowing them to express themselves in a context that evolves
- Without negatively impacting the outside of the building.
- Economically: With adaptability, a building can perform its function more efficiently, last longer, use less material, and utilize innovative technologies.
- Environmentally: The ability to adapt reduces resources and energy consumption and ensures minimal environmental disruption.

According to (Mansfield, 2009), there are three aspects for controlling the level of flexibility and knowing these items aid in increasing the level of flexibility. “Decision-makers, nature of the decision, factors of flexibility.” Two ‘hard’ and ‘soft’ factors influence flexibility. "Material standards," "Production," and "Installations" are considered soft factors, whereas "Financial aspects," "Awareness aspects," and "Planning for future changes and service life" are considered ‘hard’ factors. Furthermore, several decision-makers are involved in the construction project and are essential in increasing flexibility, including: "property owners, architects, contractors, authorities, project managers, users and clients." The level of adaptability in the building depends on how effectively these decision-makers collaborate and prioritize the soft and hard factors.

1.1.2 Factors and criteria for adaptability and flexibility

Modular components can be easily connected, assembled, and disassembled, promoting flexibility and adaptability in the overall system. Criteria for adaptable components includes five classifications (Figure 1.3)

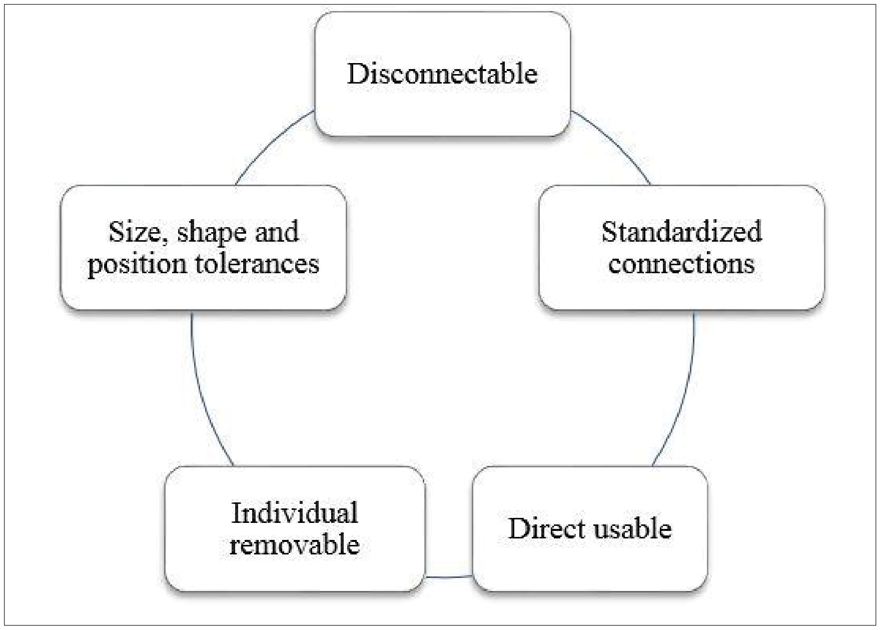


Figure 1.3 Criteria for adaptable components

Moreover, some factors can enhance the flexibility and adaptability of the building. These factors affect several aspects of construction, including the size and dimensions of components and layers, their position, task, performance, function, and the size and extent of the spaces (Manewa et al., 2016). Specific characteristics are in Figure 1.4 as being important in building design, including mobility, adjustability, scalability, versatility, adaptability, and convertibility. Elements such as walls must quickly move or adjust inside and outside a building, aside from reducing the need for demolition. Additionally, prefabricated and modular components make it easier to modify or expand spaces as needed. Additionally, by designing the building with a convertible function, different areas can serve multiple purposes and adapt from serving one purpose to becoming versatile and multifunctional. The principles of the sustainable and adaptable building design are aligned with this concept, as discussed in this thesis. A building designed in this manner can respond more effectively to changing needs while requiring less construction or demolition in the future. It also reduces the waste and energy associated with new construction and demolition. In building design, movability allows spaces to be reconfigured and adapted in response to the changing needs of occupants without undergoing extensive construction or demolition. The result is a reduction in waste and energy consumption and an enhancement of the building's overall flexibility and longevity and allows spaces to easily transition from one use to another based on convertibility in building construction. Due to this design feature, different areas can be transformed without requiring extensive construction or demolition, thus allowing for greater versatility and adaptability. Convertibility is an essential aspect of building design that enables buildings to meet the evolving needs of occupants, promote sustainability, and reduce waste and energy consumption. Overall, convertibility in building design is essential for creating structures that are not only sustainable but also capable of evolving with the needs of their occupants.

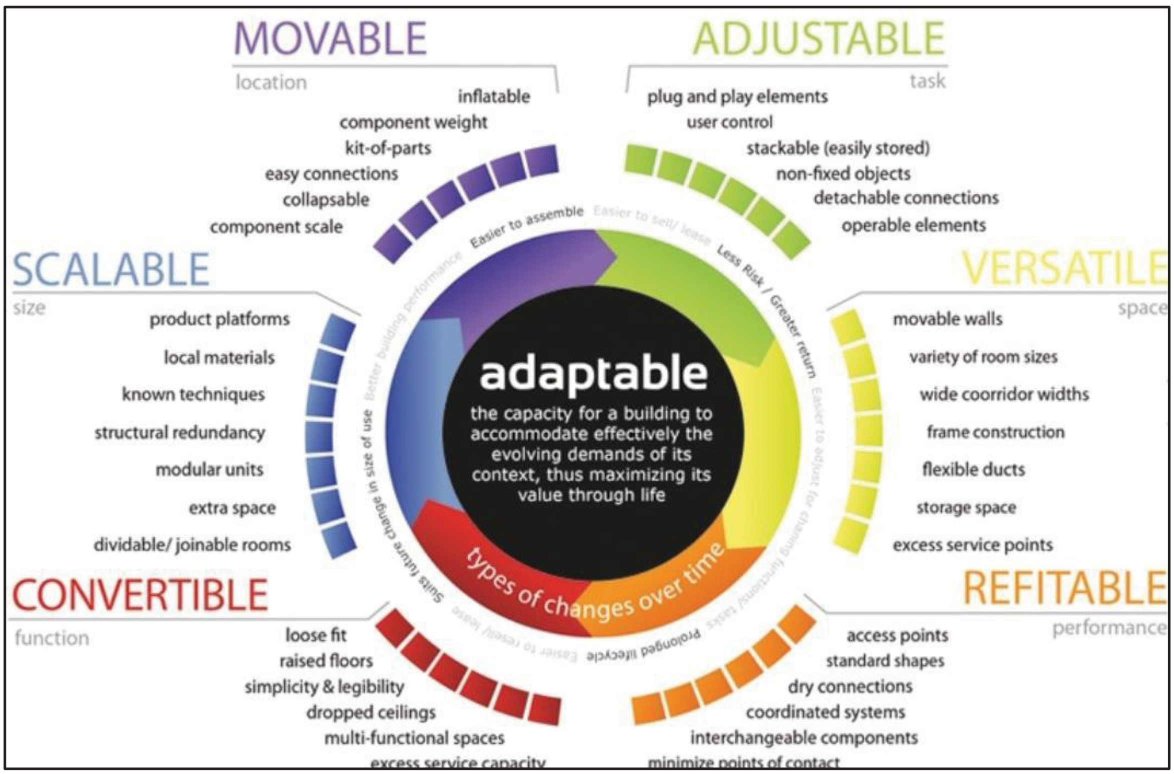


Figure 1.4 Indicators for adaptable and flexible design
of components and spaces
Taken from Manewa et al. (2016, p.7)

This approach helps in reducing environmental impact, conserving resources, and ensuring that buildings remain useful and functional for longer periods.

1.1.3 Types and factors of changes in the building

Buildings can change due to various factors, including functional, technological, regulatory, economic, and social influences. To ensure that buildings remain relevant and functional and contribute to the built environment, they must be adapted to meet evolving needs and circumstances. Throughout a building's lifespan, several types of factors contribute to changes. Changes in the building can include renovations to update the interior design, retrofitting for energy efficiency, modifications to comply with new building codes, or even repurposing the space to serve a different function. By designing for adaptability and flexibility, the building can adapt to changes, and its components could last longer (Askar et al., 2021). According to Sadafi et al., 2014, the building has had two significant internal and external alterations over the years (Table 1.2).

Table 1.2 Changes and factors of changes
Taken from Sadafi et al. (2014, p.409)

Changes	Factors of changes
Internal changes	Changes in functional requirements
	Poor maintenance or abuse of systems
	Organizational shifts
	Increases in performance expectations
	Aesthetic shifts
Environmental uncertainties	Changes in markets (Product price, Energy price)
	Changes in climate (Global warming)
	Adoption of new standards and codes
	Technological changes
	Shifts in property values

Uncertainties are one of the issues in construction that create complexity. According to Allahaim et al., 2010, there are two main reasons for uncertainty in the construction industry. Market hesitation regarding future demand and cost predictions adds to the complexity. Based on Figure 1.5, there are seven significant changes during the life cycle of a building.

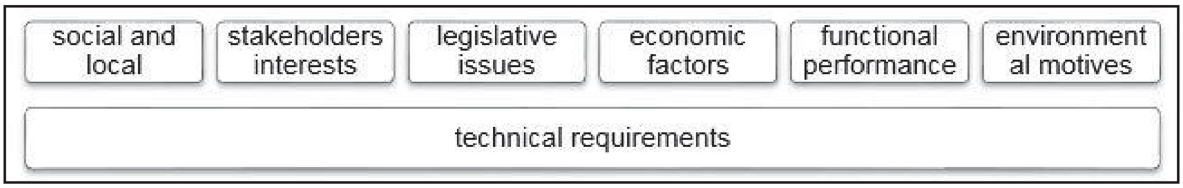


Figure 1.5 Factors of changes
Taken from Askar et al. (2021, p.2)

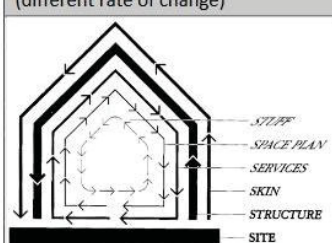
Changes in the market, such as shifts in consumer preferences, can drive the need for building changes. The evolving needs of occupants or users of a building can prompt changes. For instance, a growing workforce might require more office space, or a hospital might need to expand to accommodate an enormous patient load. Outdated technology can make a building less functional. Upgrading systems like HVAC, security, or data infrastructure can become necessary to maintain efficiency and security. Buildings in disaster-prone areas may need changes to enhance their resilience against earthquakes, hurricanes, or floods.

1.1.4 Approaches in design for adaptability

The publication "Approaches in Design for Adaptability" explores the multiple strategies employed to create products and spaces that are inherently flexible and capable of evolving. As a result of changing user's demands, environmental considerations, and technological advancements, this concept has gained traction in recent years. This philosophy emphasizes that design should not be static but rather a dynamic process that anticipates and accommodates future alterations with minimal waste or disruption. Architects and designers can craft efficient, economical, and empathetic solutions to the changing needs of humans and the environment by prioritizing adaptability. These are the approaches for adaptability that found in the literature review: shearing layers, open building and metabolism.

- Shearing layers: The concept of shearing layers emphasizes the fact that different parts of a building evolve at different rates. The core structure and site may change slowly, but interior spaces and furnishings can adapt quickly to meet changing needs or functions. To ensure that buildings remain functional and relevant over time, architects and designers can use this framework by designing the layers in a way that they could be easily separated when one of them needs to be changed. According to (Estaji, 2017), the building has six layers. Among these layers are "site, structure, skin, services, space plan, and stuff," where "site" refers to the location of the building and its surroundings. "Skin" refers to the facade, exterior walls, and elements of the building. "Structure" refers to a building's foundation and fundamental elements, such as its columns and bearings. A building's "services" refer to its vertical and horizontal pipes. The building uses these pipes for mechanical, electrical, etc. purposes. "Space plan" refers to the layout and elements of the interior of a building. The term "stuff" refers to the furniture and appliances in the building. Each layer has a different lifespan, from everyday alteration to more than 300 years, as shown in the following table. The alteration of building layers necessitates the design of a building that can be flexible (short-term changes) and adaptable (long-term changes), (Table 1.3).

Table 1.3 Building Layers and Longevity
Taken from Estaji (2017, p.42)

Shearing Layers (different rate of change)	Layer	Description	Longevity
	Site	Geographic setting, urban location	Eternal
	Structure	Foundations and load bearing elements	30 to 300 years
	Skin	Exterior surfaces (Facades)	20 years
	Services	Wiring, plumbing, HVAC systems and ...	7 to 15 years
	Space Plan	The interior layout	3 years
	Stuff	Furniture, kitchen	Daily to monthly

According to (Nakib, 2010), accessibility and circulation could be added to the previous six layers as shearing layers.

- Open buildings (OB): The open building approach promotes the separation and independence of building layers to enhance flexibility, adaptability, and long-term sustainability. It provides a framework for designing buildings that can evolve and respond to changing circumstances, ensuring they remain functional and relevant. The building has distinct layers in the OB system and integrates with other layers by flexible interfaces" (Askar et al., 2021). This flexibility aids in making interdependent layers with divergent functions that can adapt to the changes with less impact on other layers. Open building systems include "social" and "technical." Regarding "social," OB aids in fulfilling the user's needs by offering flexibility. In the " technical " aspects, the building is a system with sub-systems that OB contributes to providing recyclability and reusability in these sub-systems (Habraken, 2003). Table 1.4, indicates some definitions of "OB" from 2019 to 2021.

Table 1.4 Definitions for open building

Author	Year	Definition
Russell, P.; Moffatt, S. 2001 cited in Askar et al.	2021	"The "Open Building" term implies a notion of simple structures that easily succumb to flexibility and change over time."
Kronenburg, 2007 cited in (Julistiono et al.,)	2017	"Open building principle is a strategy that allows multi-use space to accommodate various functions. To apply this principle, during the design process, reference of future changes should be included but not to restrict flexibility by user's intervention".
etal.(2000) Li et al.	2019	"Open Building is an important and systematic approach to design and construction for adaptability in terms of combining building components in such a way as to give optimal freedom of layout and installation."

For the history of “OB” based on the (Habraken 2003) citation, the "SAR" (Foundation for Architects Research) divides a building into "base-building" and "fit-out." These two terms are "support" and "infill." He also stated that the structural support "Base building" is under the investor's control, and the flexible infill "fit-out" is up to the user's control. Base building refers to structures like columns and beams. Infill refers to the door, walls, windows, and furniture. According to (Askar et al., 2021), the "Open Building" concept can be traced back to the 1960s, when the post-WWII housing shortage led to a desire to strengthen individuals. Implementing the open building concept could be decomposed into various levels.

Generally, "support" and "infill" are two levels of decision-making in designing an adaptable and flexible building. In adapting to changes, each level has a different duration and function (Ismail and Rahim 2011). There is also a general classification for OB levels. According to (Kendall & Teicher, 2000), an open building system has three primary levels.

- ❖ Tissue level: It concerns urban planning issues and builds on a considerable body of related work in the urban environment.
- ❖ Support level: The supports provide a serviced space for occupants. A variety of technical systems or materials can be used to build them.
- ❖ Infill level: These systems gradually shift downward to lower levels as technical and organizational tasks.

- Metabolism movements: For the third approach for DfAd, 'Metabolism' is derived from the Japanese word Shinchintaisha, which signifies revitalization or regrowth and is closely related to the Buddhist concept of reincarnation (Schalk, 2014), (Figure 1.6). The Metabolism movement emerged in 1960 when an association of architects and designers drafted their radical declaration called Metabolism. It was for New Urbanism at the World Design Conference in Tokyo (Schalk, 2014). Scuderi – 2019 cited that "Archigram's Warren Chalk" designed a tower with a centralized organizational structure and attachable prefabricated modules in 1964. Afterward, Kisho Kurokawa, a metabolism architect, redeveloped this concept in Tokyo Tower in 1972. The metabolic design emphasizes interchanging parts, modularity, prefabricated components, and packages (capsules). Each element has the features of changeability and movement based on customer (user's) demand (Echavarria P 2004, cited in (Scuderi - 2019). According to Generalova et al. 2016, modular systems are helpful for "multi-stores," "low-rise," and "high-rise" construction. The high-rise modular building requires a structural core in the center as a vertical element that involves stairs and elevators. So, other 3D blocks could attach to the core. In this scenario, there are three distinct types of central structure:

- ❖ Use regulations of modular components in the fabrication of the central structure.
- ❖ By utilizing reinforced concrete.
- ❖ Fabricate an integrated central structure with reinforced concrete and steel frames.

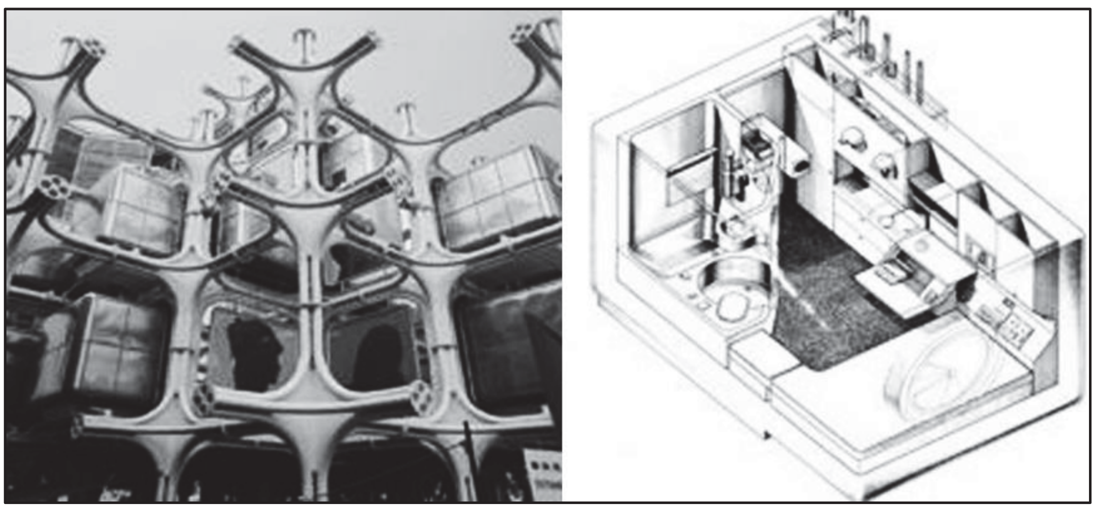


Figure 1.6 Axonometric of Capsule
Taken from Lin (2007, p.516, 517)

Modularity is a fundamental concept in Design for Adaptability, Design for Manufacturability, and Design for Disassembly. It involves breaking down a system, product, or building into modular components that can be easily assembled, disassembled, replaced, or upgraded. Also, in infrastructure and industrial investment, modular construction could gain up to 10 percent of market share and save up to 10 percent on construction costs. In this process, an offsite factory fabricates standardized elements of a structure, which are subsequently assembled on-site (Bertram et al., 2019). In sustainable construction, designing modular elements of a building simplifies the process of disassembly, reusability, versatility and increasing adaptability and flexibility (Askar et al., 2021). Also, modularity is used to increase quality, reduce costs, and reduce schedules (Bridi et al., 2019). Table 1.5 illustrates some definitions of modular coordination (MC), modularity and modular components. Modular components are parts of a structure or system that are designed to be easily assembled, disassembled, replaced, or upgraded. These components are typically standardized and prefabricated in a controlled environment, such as a factory, which allows for better quality control and precision manufacturing. In the context of construction, modular components can significantly enhance flexibility and efficiency. They allow for the rapid construction and modification of buildings, as the components can be quickly assembled on-site. This method not only speeds up the construction process but also reduces waste and minimizes the environmental impact. Additionally, the ability to easily replace or upgrade parts of the structure means that buildings can be more easily maintained and adapted to changing needs over time. Modular construction has the potential to capture a significant share of the infrastructure and industrial construction markets, with estimates suggesting it could account for up to 10 percent of these markets. Furthermore, it can lead to substantial cost savings, reducing construction costs by up to 10 percent compared to traditional methods. This is largely due to the efficiencies gained from offsite fabrication and the reduced labor and time required for on-site assembly. Overall, modular components offer a versatile, cost-effective, and sustainable approach to construction and design, making them an increasingly popular choice in various industries.

Table 1.5 Definitions of modular coordination, modularity and components

Modular coordination (MC)		
Authors	Years	Definition
Patelia et al.	2013	“a concept of coordination of dimension and space, in which building components are dimensioned and positioned in a term of a basic unit or module, which is also known as 1M, and which is equivalent to 100 mm (about 3.94 in).”
Patelia et al.	2013	“It is the international system of dimensional standardization in building. MC is internationally accepted by the International Organization for Standardization (ISO).”
Module		
Author	Years	Definition
Patelia et al.	2013	“A unit of measurement means standardized and easily fit components.”
Patelia et al.	2013	“It is a fundamental unit of size. The term module is derived from the Latin modules, which in English means "Small dimension."
Modularity		
Authors	Years	Definition
Baldwin and Clark, 1997	2014	“Modularity can be understood as the perspective on which a product uses subsets, called modules, which operate as an integrated whole.”

By applying the modular system to a building's design, the designer, engineers, and manufacturer can identify the dimensions and scales of elements and assemblies, installation, details, and service systems. Patelia et al., 2013 mentioned that MC has some benefits in the construction:

- Make integration between designers, manufacturers, and providers of services activity.
- Using standardized elements in dimension and scales.
- To improve the dimensions of standard building components.

- Enhance the speed and quality of construction.
- Reduction in time and cost and material consumption

According to Patelia et al., 2013, there are some essentiality and fundamentals in MC.

- Basic modules: It is a basic unit of measurement.
- Modular dimensions involve a wide range of flexible dimensions that fulfil aesthetic and structural dimensions.
- Planning modules and placing components: This refers to the location of elements in vertical and horizontal orientations and lines.
- Modular Grids: It includes a network of lines in three directions, X, Y, and Z, with specific distances.
- An essential modular Grid refers to the smallest network of lines in modular buildings.
- Multi-Modular Planning Grid: it includes a combination of different Grids.
- Tartan Grid: a combination of different Grids with regular distances and spaces.
- Square and rectangular Grid: Grids just in the shape of a square or rectangle.
- Preferred dimensions: These are specific modular dimensions for a unique project. Modular elements have specific sizes, such as 30 M = 3 X 10 or 60 M = 3 X 20. Each M is 100 mm (about 3.94 in).
- Tolerance: For the component to fit within the grid space and have the correct position with less error, tolerance is needed.
- Manufacturing tolerance: Reduces the possibility of dimensional errors and inaccuracy in the manufacture of components.
- Positional tolerances: The position of installed elements does not shift from their assigned positions.
- Joint tolerances or gaps: Reduce the fluctuation in joint thickness.

The product should be independent so that one alteration does not influence the other. Also, there are three significant aspects of modularity in final products through modularity (Rodrigues et al., 2014):

1. Modular components are independent.
2. Via interfaces, the integration of independent modular elements is possible.

3. Standardization assists in ensuring that modules are compatible and adaptable to changes.

To develop innovative products and to increase flexibility and use and reuse elements, modularity has the potential to address the issue. Also, modularity includes three types: product, process, and supply chain (Peltokorpi et al., 2018, cited in Bridi et al., 2019). "Product modularity" is the ability of a product to separate into parts and components depending on how the product is designed (Gershenson et al. 2003). "Process modularity" entails common interfaces and standardized operations as standardized manufacturing, delivery, and assembly processes (Lennartson and Björnfot 2010). "Supply chain modularity" describes an organization of companies that convert raw materials into supplies, products, or modules, including means of distributing them. (Cheng et al. 2010). Modularity has some advantages in each domain (Lennartsson & Björnfot, 2010):

❖ Product Modularity:

- Modular products allow components to be repaired easily
- Modular products allow components to be enhanced and extended
- Modular products enable standard interfaces to reduce complexity and make interaction between independent components
- Easy system evaluation is made possible with a modular product
- Ensure that functional details are helpful for accurate technical information.

❖ Process modularity:

- A modular process makes it possible to utilize standard innovative production.
- A modular approach enables simultaneous assembly to reduce time.
- A modular process enables standardization.

❖ Supply chain modularity:

- A modular supply chain can cover distant locations between demanders and suppliers of material and production.

- Modular supply chains allow independent organizations to function and determine the main level of organization based on their function and knowledge.
- Modular supply chains promote communication independence.

For example, the Raines Court apartment block was the first modular housing production in the UK in 2003. It comprises zinc panels that are attached to frames to conduct the façade. Also, it involves a modular structure that is easily adaptable and changes (Figure 1.7).

Figure 1.7 Front and Rear Facade of Raines Court
Taken from Ismail and Rahim (2011, p.13)

1.2 Design for manufacturing and assembly (DfMA)

To create adaptable buildings, Design for Adaptability, Design for Manufacturability, and Design for Disassembly are essential principles that aim to make buildings more accessible to modify, manufacture, and eventually disassemble. By Beadle et al. 2015, there is a framework for building adaptability. As illustrated in Figure 1.8, the plan is extendable at the first stage of designing for adaptability. It is possible to shrink or expand the arrangement and dimensions of the plan as needed. During the process of utilizing the building, the spaces are flexible and can be adapted to serve a variety of purposes. There is the potential for all components to be changed or adapted to meet the needs of innovative technologies. Replacing or removing these components has less impact on the other components. Finally, the demolition or material usage are possible by reusing or reconstructing.

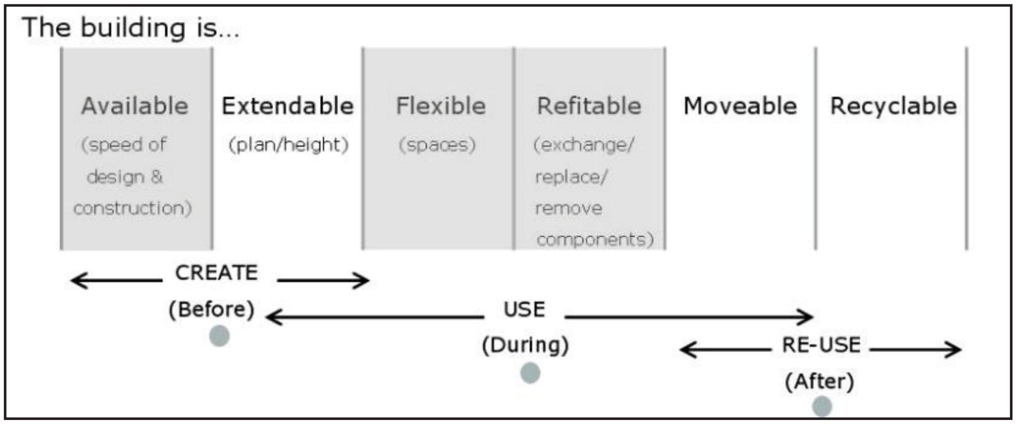


Figure 1.8 Adaptable Futures Framework
Taken from Beadle et al. (2015, p.2)

According to Scuderi - 2019, some procedures have been developed to improve flexibility and adaptability. He classified the design for flexibility into two categories. Figure 1.9, illustrates diverse procedures to increase flexibility, starting with "architectural, social, and functional factors," followed by "structural, technological, and construction factors."

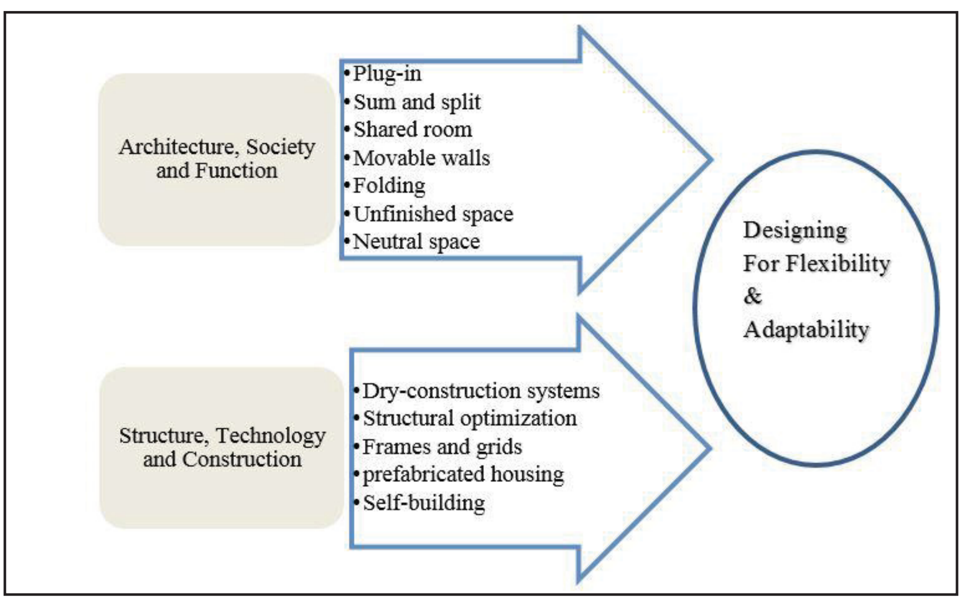


Figure 1.9 Procedures for increasing flexibility and adaptability
Taken from Scuderi (2019, p.2 - p.5)

In the following based on Scuderi's 2019 citation, there are some explanations for these procedures:

- The plug-in procedure aids in fulfilling user's requirements by expanding spaces or adding new modular components.
- Sum and split are long-standing procedures aiming to convert monofunctional spaces into multifunctional ones. Expand or shrink the size of spaces by blending or dividing them. In terms of convertibility, accessibility and services are crucial.
- The folding procedure with folding internal and external elements aims to hide or expose some parts of the internal and external spaces according to the user's demand.
- Unfinished space aids in making more user enterprises in the design process.
- Neutral space is essential for non-label space without any specific function.
- Dry-construction systems involve lightweight, interdependent components which are easy to assemble.
- Structural optimization aids in optimizing the weight and simplicity of modular structural components.
- Frames and grids refer to structural components which can adapt to long-term or short-term changes. Both immovable and movable elements are in an adaptable structural system.
- Prefabrication aids in enhancing the level of flexibility and adaptability. Meanwhile, recently, the components should have the potential to be reused or disassembled without any demolition.
- Self-building refers to having the most customer involvement in design and production. The users are self-builders who try to fulfill their requirements directly with their designers and contractors. In addition, technological apparatus, materials, and methods are used, such as photovoltaic cells.

Furthermore, "framing" is one of the most appropriate procedures. This procedure provides more plan and structure customization options and fulfills customers' demands (Scuderi, 2019). Besides a flexible design for "plan" arrangement, utilizing technology and novel methods in designing and fabricating flexible "structure" elements should be considered.

- PLAN: According to Malakouti M. et al., 2019 cited in (Askar et al., 2021), the open plan lacks physical and mechanical restrictions. So, an open plan should be designed to make an adaptable interior space that is interdependent and less affects exterior components. They also stated that open plans are convenient for functional alteration, and commercial buildings seem to have open plans to be more adaptable.
- STRUCTURE: Structural adaptability is "The building structure's capacity to change to the structure itself, with or without only small consequences for the remaining building story" (Gijsbers, R 2006, cited in (Askar et al. 2021). In the DfA, the design "adaptive exoskeleton" is a procedure to enhance flexibility and adaptability by extending the life span of the buildings (Figure 1.10). This procedure aids in optimizing the structure as an external skin, increasing sustainability, decreasing energy consumption, and improving internal quality. This structural system involves several types of modular components with interdependent features. Dry connections, steel frames, reusable materials, and modern technologies such as roof gardens and detachable terraces are standard in exoskeleton systems (Scuderi – 2019).

Figure 1.10 The exterior of Morpheus hotel
(Source: https://www.architecturaldigest.com)

Also, Nakib, 2010, stated that the support level should be flexible and divisible: It should be possible to extend vertically or horizontally or divide into different functional units without affecting the building's function or coherence (Figure 1.11).

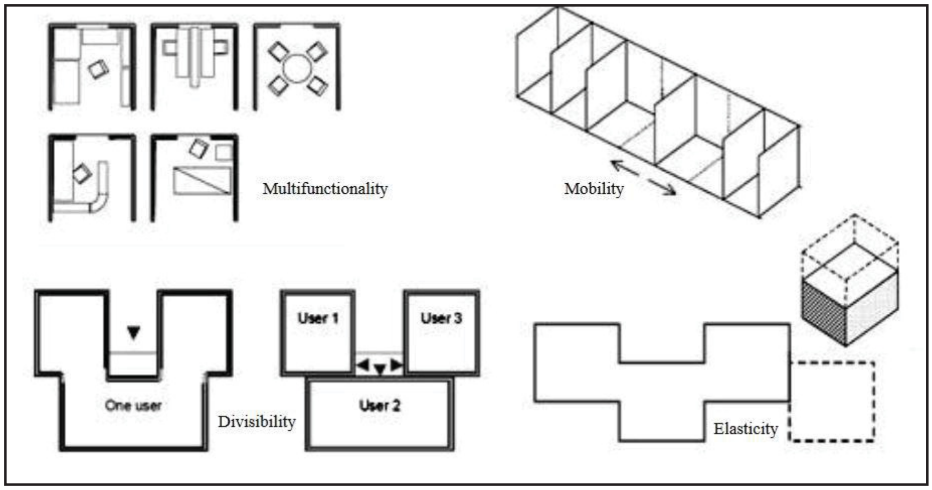


Figure 1.11 Multi-functionality, mobility,
Divisibility, elasticity
Taken from Nakib (2010, p.5)

- Façade: According to Del Grosso and Basso, 2010, the skin of buildings refers to the coverage of the building. Skin could have an interactive and sustainable function regardless of its structure. A kinematic façade is an example of being interactive and adaptive. They also categorized a Kinematic façade into “deployable” and “rigid links” based on alteration and conversion (Figure 1.12).

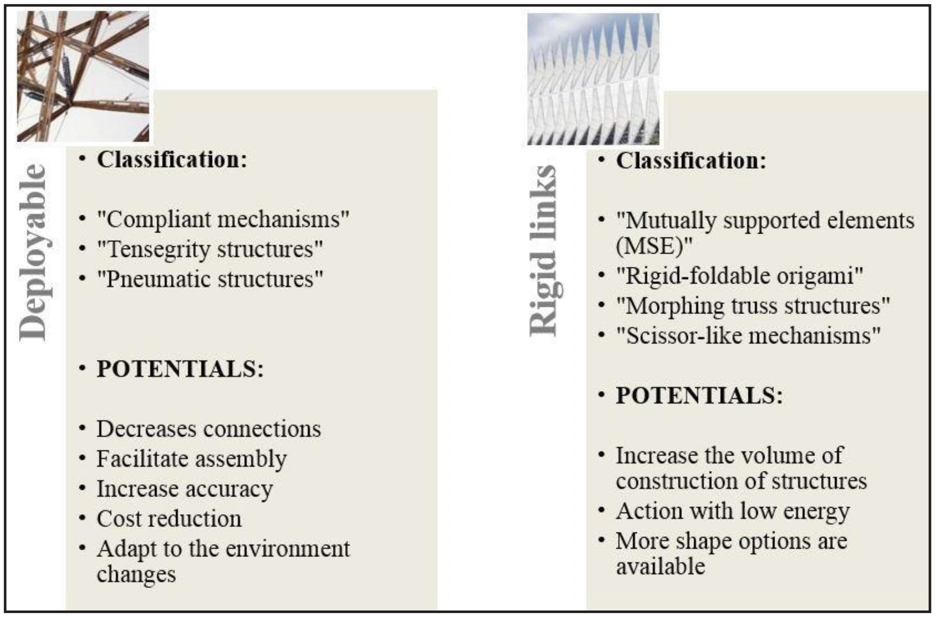


Figure 1.12 Classifications of the kinetic façade
Taken from Del Grosso and Basso (2010, p.2 - p.4)

1.3 Digital design and digital fabrication

There is a need for innovative procedures in design and construction due to the adverse effects on the environment and lack of productivity in architecture (Menges 2018a cited in Schwieger, 2019). Operators use digital technology to automate operations and methods to create higher efficiency in prefabrication and on-site construction (Knippers et al., 2021). Automating manufacturing, fabrication, and assembly processes is also a key element of digitalizing design and construction (Schwieger, 2019). Digital design and fabrication techniques play a pivotal role in creating adaptable buildings. They enable architects and designers to envision, plan, and construct buildings with high precision and flexibility. There are several ways in which digital design and fabrication techniques are practical for the design of adaptable buildings:

1. Building Information Modeling (BIM): BIM is a digital technique that allows architects and engineers to create detailed 3D models of buildings, including all their components and systems. It facilitates the coordination of various building systems and helps visualize design concepts and their impact on adaptability. BIM also enables the simulation of future modifications and additions to the building.

2. Parametric Design: Parametric design involves using algorithms and mathematical relationships to create complex and adaptable designs. Architects can create design parameters that respond to changing conditions, such as environmental factors or user needs, allowing for real-time adjustments to the building's design.
3. Generative Design: Generative design uses algorithms to explore various design possibilities based on specified criteria. Architects can use generative design to optimize layouts and configurations for adaptability and functionality.
4. Digital Fabrication and Prefabrication: Digital fabrication technologies like 3D printing, CNC machining and robotic assembly enable the precise production of building components. Prefabrication of modular building elements in controlled environments ensures high-quality construction and reduces on-site labour and waste.
5. Virtual Reality (VR) and Augmented Reality (AR): VR and AR technologies allow designers and clients to experience and interact with building designs in immersive and real-time environments. These technologies aid in visualizing how adaptable features work and how they can be modified.
6. Computational Analysis: Computational analysis tools simulate various building performance aspects, such as energy efficiency, structural integrity, and environmental impact. These analyses inform design decisions and help optimize building performance while considering adaptability.
7. Digital Prototyping: Digital prototypes can be created and tested before physical construction to ensure adaptable components and systems function as intended.
This production aids in reducing the risk of costly errors during construction and modification.
8. IoT Integration: The Internet of Things (IoT) enables the integration of sensors and smart systems that provide real-time data on building performance. This data informs adaptive responses to changing conditions, such as optimizing energy or space utilization.
9. Building Performance Simulation: Digital simulations model how a building perform under different scenarios, allowing designers to anticipate and plan for adaptability requirements. Simulations can predict how occupancy, climate, or technology changes affect building performance.

10. Digital Documentation and Records: Maintaining a digital record of a building's design, construction, and modifications aids in managing its adaptability over time. - It provides a comprehensive history of the building's components, systems, and maintenance.

By optimizing design processes, ensuring precision in construction, and providing tools for ongoing monitoring and modification, digital design and fabrication techniques enable architects and designers to create adaptable buildings. Due to these technologies, buildings are likely to be able to adapt and respond to changing user needs, environmental factors, and technological advances in the future.

Digital technology is rapidly advancing and is being applied to the construction process by architects and engineers. For instance, computer-aided design (CAD) enabled designers to convert drawings into a digital format (Smorzhenkov & Ignatova, 2021). In architecture, the computer is used as a digital drawing board, allowing the user to modify, reproduce, and enhance the accuracy of the drawing (Bazalo & Moleta, 2015). Figure 1.13, illustrates a comprehensive, integrative computational strategy's digital chain to modernize design, construction methods, and system architecture as CAD, CAE, CAM, CAC, CAFM and CADC/R (Schwieger, 2019).

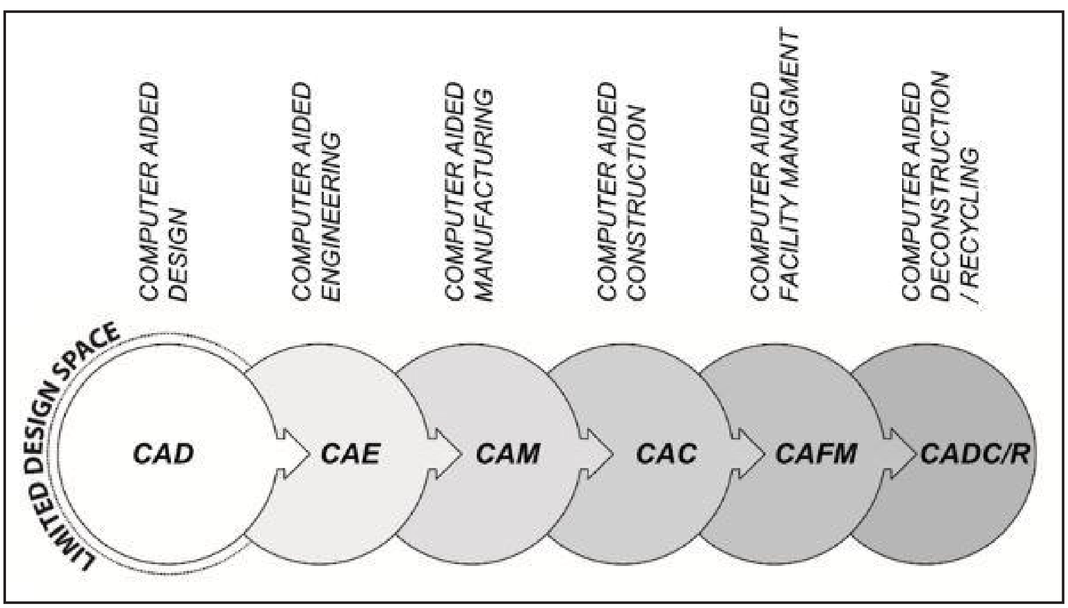


Figure 1.13 From digital chain to digital feedback
Taken from Schwieger (2019, p.224)

According to Wojtkiewicz, 2014, in human history (paintings, architecture, design art, and other historical activities), generative systems are practical in design. He also stated that to produce a design solution, designers must examine various approaches, methodologies, geometries, shapes, materials, layouts, and combinations. Having a range of alternatives makes selection and comparison possible. For digital design techniques, generative design affects the design process. It contributes to converting creative ideas into projects, enhancing quality, productivity, and accuracy. In addition, it aims to use multiple design techniques (V Smorzhenkov & Ignatova, 2021). Also, algorithmic or generative design are approaches for designing physical or digital objects based on creating parametric models. Some definitions exist for generative design (Smorzhenkov & Ignatova, 2021), (Table 1.6). Through the integration of advanced computational techniques generative systems have increasingly influenced contemporary design practices. Through the use of these systems, it is possible to create complex and innovative designs that would be difficult to achieve by using traditional methods.

Table 1.6 Definitions of generative design

Authors	Years	Definition
Ma et al.	2021	“Generative design (GD) as a rule-driven iterative design process is based on algorithmic modelling and parametric modelling to automatically explore, iterate, and optimize design possibilities by defining high-level constraints and goals.”
Agkathidis	2015	“GD is a cyclical process based on a simple abstracted idea, which is applied to a rule or algorithm.”
Wojtkiewicz	2014	“Generative synthesis systems are systems of combined mechanisms that are capable of creating alternative compositions that address design problems, express design view, and additionally, offer a huge scope of satisfactory solutions.”

GD has some advantages in the design process. Using GD, human designers can investigate and iterate design options and determine the optimal solutions for decision-making (Ma et al., 2021a). Also, GD can evaluate design options for any AEC project (e.g., architectural design, structural design, interior design, urban design, urban planning.). Figure 1.14 shows a GD process. An idea, rule or algorithm drives GD as a cyclical process, and the source code generates sequential output through a computer program. A recursive loop returns data, allowing the designer to modify the algorithm and source code. The process involves iteration based on interaction between the designer and the design system.

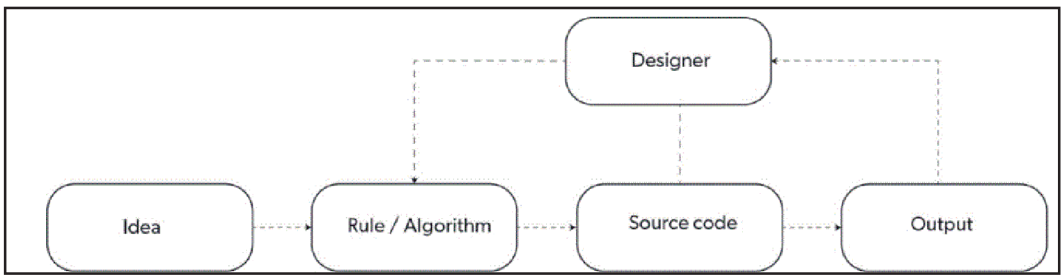


Figure 1.14 Generative design process diagram
Taken from Agkathidis (2015, p.3)

For creating a generative design and model, the following steps are typically followed (Nagy, D et al., 2017, cited in (Ma et al., 2021a)):

- Setting design objectives
- Identify design restrictions
- Determining algorithms
- Put the GD into operation and program
- Execute the GD
- Based on objectives and restrictions, revise and alter the generated parametric models according to the needs.

There are some novel methods of digital design that aid in design for adaptability. In these methods, the arrangement of modular components is essential. For example, ‘discrete design methods’ aim to develop a completely "digital" architecture from conception to fabrication. Through this approach, building blocks are designed for robotic assembly into a wide range of structures (García et al., 2020). SL-blocks are octal cubes made up of two tetra cubes connected by sides. Among octa cubes, the SL block provides the widest variety of combinations (Wibranek et al., 2021). Some advantages of using an SL block include reversible connections, various sizes and dimensions, and dry connections. (Figure 1.15).

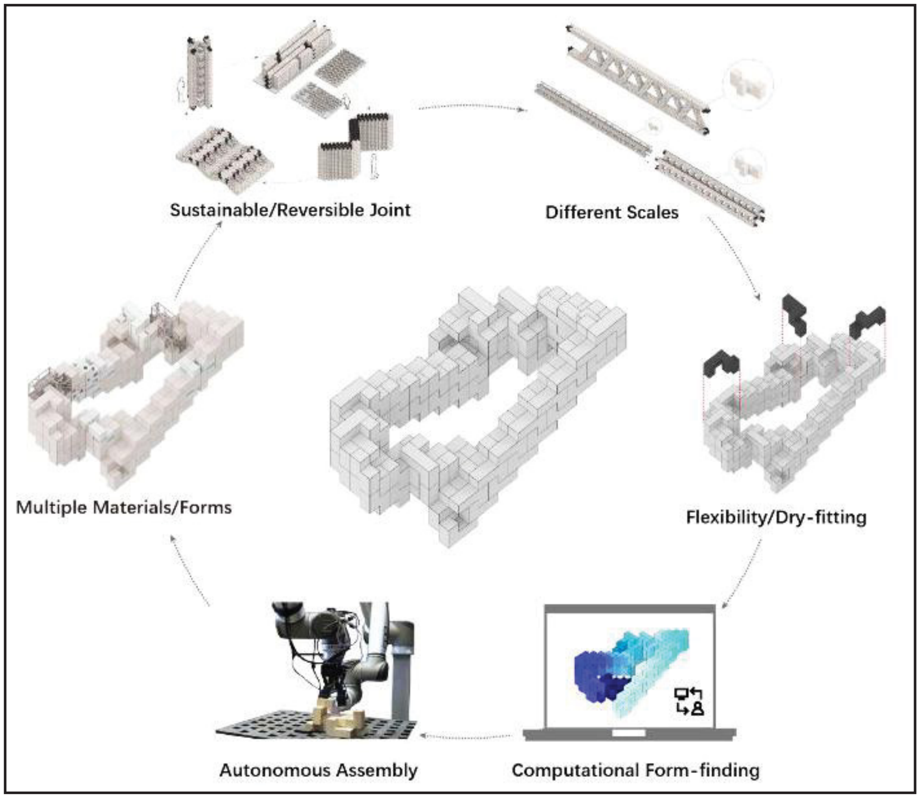


Figure 1.15 Advantages of SL-block in modular design
Taken from Wibranek et al. (2021, p.28)

According to Ma et al., (2021a), the tools in digital design are in two extensive categories:

- Visual programming languages (VPLs): Visual programming languages enable users to construct and develop programs by interactively modifying visual elements. VPLs are software such as Grasshopper and Dynamo.
- Textural programming languages (TPLs): Programs are in any programming language that utilizes lines of text, code, symbols, and predefined syntax. TPLs could be Python.

In addition, Ma et al. (2021a) stated that TPLs and VPLs tools offer operational efficiency, user-friendly interfaces, graphic representations of processes, adaptability to changing requirements, and significant productivity improvements. According to the scheme, a generative design can generate two artifacts (Figure 1.16). One of them includes the principles of interlocking blocks. The element may be static. There is a stickiness to the walls and floors. They do not move after assembling and settling in a place. It is easy to replace new parts during the disassembly process. The second artifact has the potential of kinematics. Designers can use both vertical and horizontal surfaces. In addition, they can expand the size, width, and length of spaces. It is possible to convert monofunctional spaces into multifunctional spaces with both artifacts.

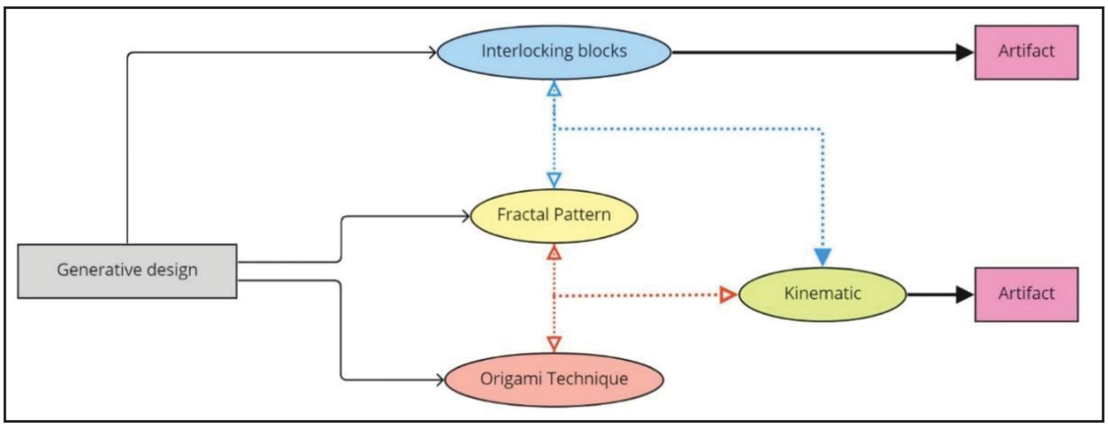


Figure 1.16 The key concept of static and dynamic artifact

The following scheme (Figure 1.17) indicates the relation of digital techniques. In the kinematic process, the mechanism are essential. In the following process, defining an origami technique is beneficial. It aids in streaming the complexity of movement. Also, the regulation of movement can be analyzed and optimized. The potential of fractals, including repetitive and standard shapes, can increase the flexibility of the origami technique. The interlocking block is a way of using fractal patterns by designing them based on the disassembly process.

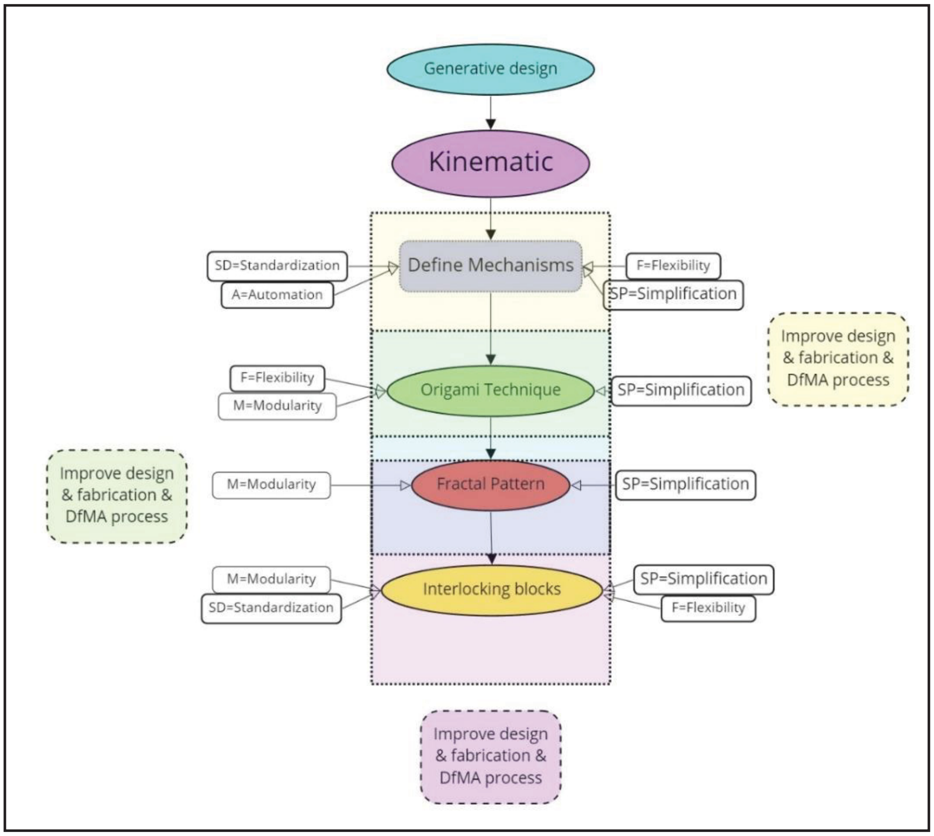


Figure 1.17 The generative design techniques

In the figure 1.18, a fractal pattern with rules and algorithms generates the codes by using parametric tools. There are some mathematical rules, such as the golden rectangle, that aid in reducing complexity and increasing standardization. Standardization and dividing parts are part of the concept of modularity in the product process. After this part, the pattern should be analyzed and optimized. Using origami to simulate the movement of angles, linkage, and connections aids in achieving an optimized movement for generating a dynamic pattern based on kinematic rules (Figure 1.18).

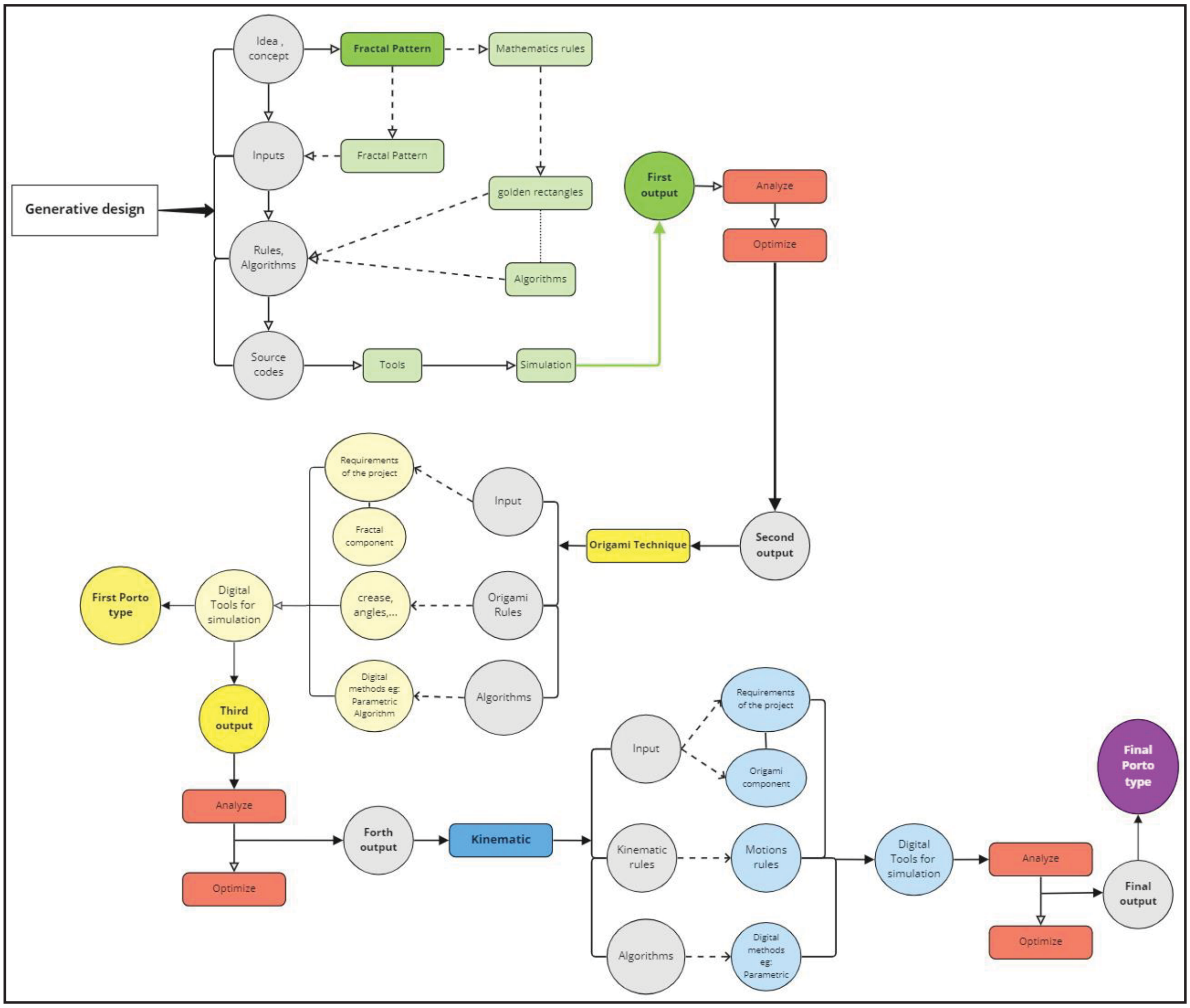


Figure 1.18 The process of digital design- synthesis based on the literature review

According to Figure 1.19, a building as a system includes subsystems such as space plans and services using the modularity concept. Element and connections are two significant items in the adaptable design of layers. The mechanism and prototyping aid in implementing movements and testing the functions of connections.

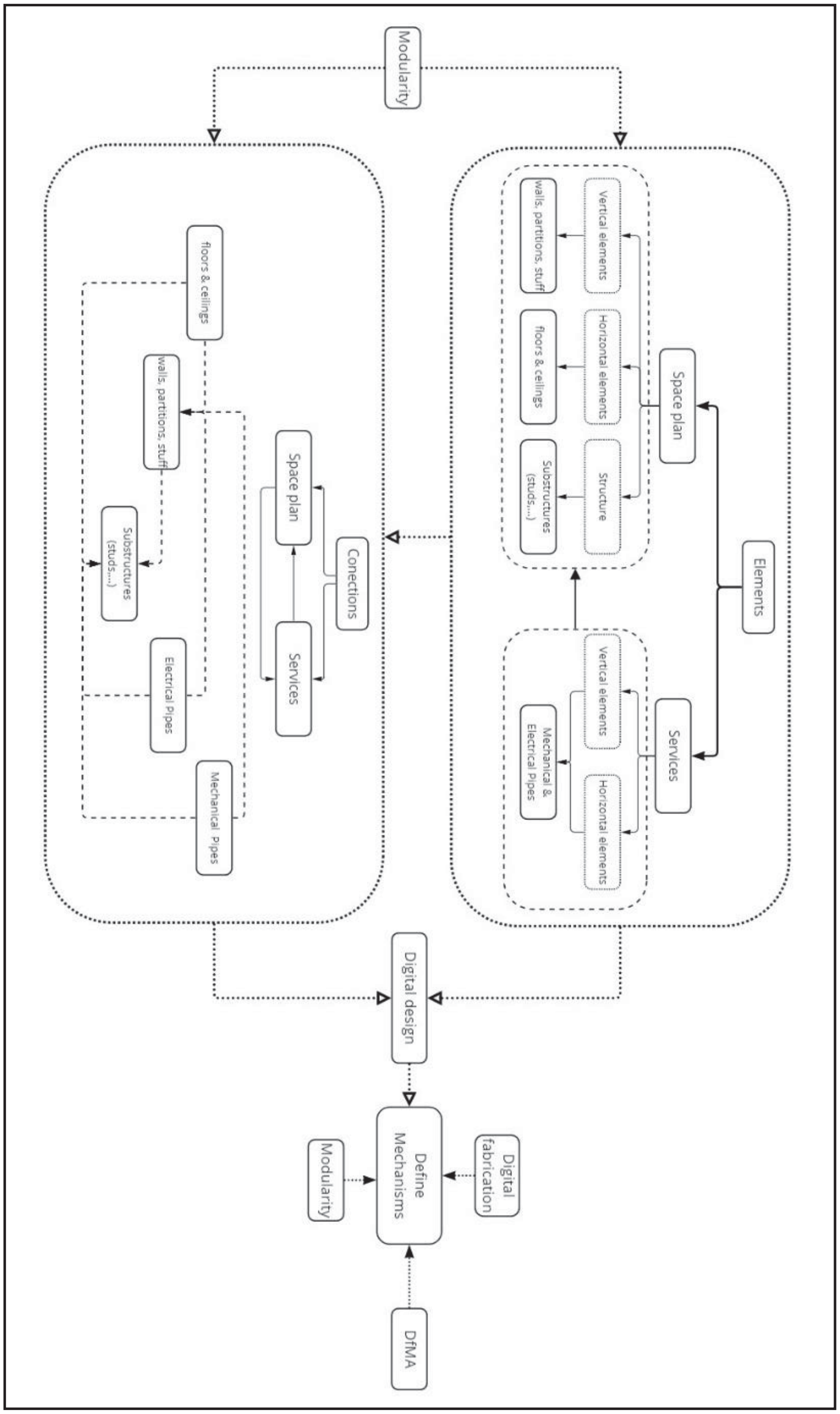


Figure 1.19 Impact of modularity and digital design on the level of adaptability in designing space plans and services

Tools such as 3D printing and robots can assist in producing complex elements. The use of digital fabrication contributes to the development of architectural design techniques. Dfab is numerically controlled manufacturing (Graser et al. 2021). Engineers, architects, and construction companies can achieve higher levels of efficiency, eco-friendliness, and creative design processes (Graser et al. 2021). In addition, they noted that Dfab methods offer greater flexibility than traditional construction processes. The automation technology includes computer-aided design, automated driving, and robotic assistance. (Chea et al. 2020) According to Anna & Saurav, 2020, fabrication refers to augmentation and "subtraction." In augmentation, robots, lasers, and 3D concrete printing (3DCP) make it possible to create 2D and 3D objects of architectural and structural components. A concrete 3D printing process involves the deposition of concrete or mortar. As a result, several centimetres of layer’s thickness (Graser et al. 2021). Incorporating robots with human workers can increase efficiency when addressing robots' potential as tools in DFAB (Hagele et al. 2004, quoted in Afsari, 2018). Fryman and Matthias, 2012 quoted in (Afsari, 2018)**,** there is some potential for collaboration between humans and robots, such as:

- They stop the robot from moving when the worker is in the collaborative workspace.
- Worker control of the robotic arm is possible.
- Keeping track of the robot's speed and separation from the worker is possible.
- Robots are in areas where human-robot interaction is possible because of their sensor capabilities and performance limitations.

The use of automation and robotics is widespread in developed economies (Figure 1.20). Construction can reduce labour costs by 30% by introducing and applying machines. It may be cost-effective to use innovative technology to create building components such as concrete walls, slabs, surfaces, and flooring to improve the quality of the building (Akinradewo et al. 2021). The installation of internal panels, windows, and surface coatings in interior buildings by robots is applicable (Chea et al. 2020). Architects, providers, and builders must participate in the prefabrication process regarding the dimensions of standard modular elements (Patelia et al. 2013), (Figure 1.21). Automation in the installation process increases efficiency and ensures precise and accurate placement of internal panels, windows, and surface coatings, resulting in a higher-quality finish for interior buildings.

Figure 1.20 Case Study for the Design and Production of Concrete 'Pop-up' Structures
Taken from Vazquez & Jabi (2015, p.9)

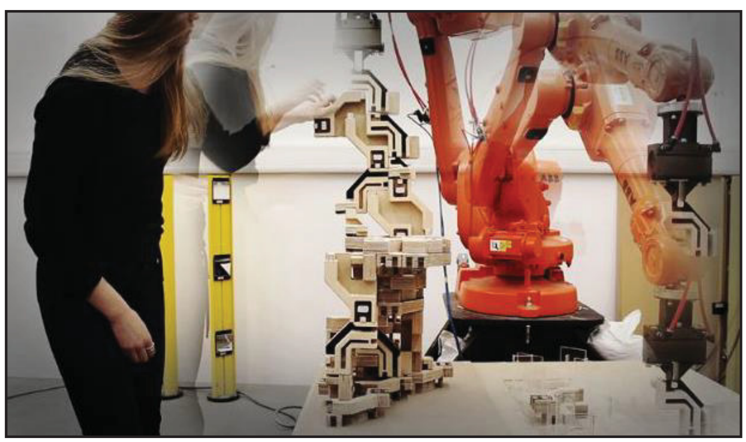


Figure 1.21 Interaction with the robot
Taken from García et al. (2020, p.37)

Digital fabrication is crucial in creating adaptable and flexible buildings by enabling advanced construction techniques and innovative design approaches. Here are several critical points in such buildings:

- Mass Customization: Digital fabrication technologies, such as 3D printing and CNC machining, allow for the cost-effective production of custom-building components (Brandão et al., 2017).
- Modular Construction: Modular construction, made possible by digital fabrication, involves assembling pre-fabricated components that can be easily reconfigured or expanded (Vujović et al., 2017).
- Responsive Building Skins: For example, facades with adjustable louvres or solar panels can adapt to changing sunlight, improving energy efficiency (Holstov et al., 2017).
- Prefabricated Components: Digital fabrication allows for precise manufacturing of building components off-site. These components are ready for transportation and assembly, which are practical for reducing construction time and waste.
- Robotic Construction: Robotic fabrication techniques have assembly potential with high precision (Ilhan et al., 2019). Robots aid in the maintenance and reconfiguration tasks in adaptable buildings.
- Additive Manufacturing: 3D printing aids in creating intricate and customized building elements, such as furniture or interior fixtures, with the potential for modification (Sakin & Kiroglu, 2017).
- Resource Efficiency: Digital fabrication can optimize material usage, reducing waste in the construction process. Additionally, it can support the use of sustainable materials and building practices (Hu et al., 2020).
- Flexible Interiors: With digital fabrication, it's possible to create modular interior spaces with movable walls, partitions, and furniture. This flexibility allows occupants to adapt the space to their changing needs (Nakib, 2010).

In summary, digital fabrication technologies provide architects and builders with the tools to create adaptable and flexible buildings that respond to changing requirements, promote sustainability, and enhance occupant comfort and usability. These technologies are at the forefront of modern construction practices, driving innovation in architecture and design. The following scheme (Figure 1.22) indicates a DfMA process into DfA and DfM processes. Both use modularity principles to minimize the parts and generate independent elements. Before sending the artifact to fabricate on a large scale, the production of small size on a small scale is practical to indicate the movement of the artifact.

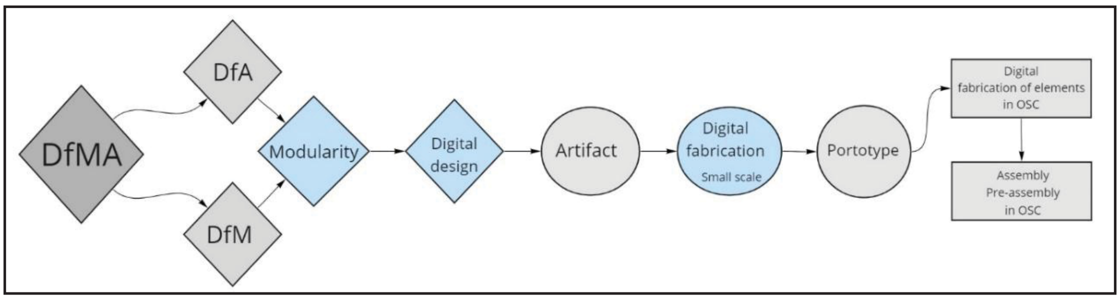


Figure 1.22 General DfMA process by using digital design and fabrication

1.4 Nature inspired pattern

Based on the research theme, origami is a part of digital design technique. It aids in enhancing the level of flexibility in design and manufacturing. Some types of origami are practical in design. Such patterns are: “Accordion,” “quad origami pattern,” “crease pattern,” “Yushimora,” and “Moira.” (Table 1.7). The art of origami has evolved from traditional Japanese folk art to a contemporary design strategy for architecture and products (MARCO HEMMERLING, 2011). Most origami techniques, such as Miura-, tesselation-, or waterbomb folds, allow the overall shape for kinetic transformation with stability. In this sense, spatial patterns are physical parametric models that modify their internal components in response to external factors and conditions (Kaczynski, 2013). (Vlachaki & Liapi, 2021).(Schenk, 2012). (Guo, 2022).(Sitnikova et al., 2018).(Buri & Weinand, 2008).(Jackson, 2019).

Table 1.7 Origami-based design

Origami-based design *(design outcomes from 2011 to 2021)*					
Authors	**Year**	**Types of origami patterns**	**Applications**	**Digital design methods**	**Specifications**
Jules, Lechenault, & Adda-Bedia	2021	Accordion	Design by controlling the pattern of creases and the rest angle and stiffness of the folds	1.Finite element methods (FEM) with the software COMSOL 2. MUMPS algorithm	1. Non-zero Gaussian curvature 2. Saddle-shaped configuration 3. Auxetic deformation 4. A random pattern of creases 5. Elasticity based on the material mechanical properties
Dudte, Choi, & Mahadevan	2021	Quad origami patterns	Megastructures at any scale	Additive algorithm	1. Four-coordinated vertices 2. Quadrilateral faces 3. Rigid-foldable panels 4. Flat-foldable panels 5.
(Vlachaki and Liapi 2021)	2021	Crease pattern scissor-hinged Yoshimura CP Polygon flasher CP	1.Rapidly erected shelters, deployable structures that respond to weather changes, foldable solar panels 2. Applied to ideal zero-thickness surfaces	1.Kinematics in Grasshopper 2.Parametric design	1. Rigid foldability 2. convex and concave folds 3. flat foldability 4. scalable mechanisms of plates and hinges 5. unified and synchronous movement of all creases

This table presents a comprehensive analysis of the applications of origami patterns in architectural design, specifically focusing on the adaptability and performance of these patterns when integrated with digital design methods.

Table 1.8 Origami-based design

Authors	Year	Types of origami patterns	Applications	Digital design methods	Specifications
MARCO HEMMERLING	2011	1. Miura 2. Tessellation 3. Waterbomb	1.highly adaptive and performative design model 2. high degree of freedom for the designer 3. adaptive wall system that can react on changing sun loads	Parametric Algorithm	1.gradual transformation in between 0° and 120° by changing its height at the same time
Kaczynski	2013	1.Folded thin-gauge plastics as semi-rigid formwork 2. Non-rigid textiles	1.flexible formwork processes 2. tension-resisting formwork 3. a full-scale, site-cast, reinforced concrete totem	programming language (Pseudo-script)	1. complex geometries
Shen & Nagai	2017	1.Computation geometry folding 2. Manual folding techniques (Rigid Folding, Curved Folding) 3. Yoshimura pattern 4. Miura Ori pattern 5. Diagonal pattern	1.Possessing creative architectural structure with advantageous load-carrying capabilities 2.Generating esthetic & deployable architectural form	Parametric tools	1. Linear Additions 2. Radial Additions 3. Two/Tree Hinged 4. Cylindrical Folded Structure 5. Pyramidal Folded Plate Structure 6. Polyhedral Folded Plate Structure
Tsiamis, Oliva, & Calvano	2018	1. Miura 2. Compliant Mechanisms 3. Lamina Emergent Mechanisms	1.increased stiffness of folded sheets 2.design free-form architectural surface structures	1.Kinematics 2.Algorithmic design 3. Kangaroo (for digital simulation of fold folding)	1. The auxetic nature 2. Paraboloid shape 3. Arch shape 4. Quadrangular mesh 5. Crease pattern 6.
(Meloni et al. 2021)	2021	Miura Kresling Flasher Waterbomb Yoshimura	1.solve mathematical problems for the design and optimization process such as the specific material stiffness or thickness 2.create an artificial transformation between target geometries through folding 3.dynamically change the structural integrity of a design 4.increased complexity of building skin elements 5.provide enhanced structural performance, reduce energy demands and develop adaptive and climate responsive designs 6. low energy actuation for structures with few degrees of freedom, possible self-actuation, and controlled motion	1.Algorithms 2. FEM simulations and OMTO, Galapagos, Octopus for optimization 3.kinematic analysis 4.Crease pattern tools such as EOS and ORIPA, TreeMaker, Rhinoceros3D/ Grasshopper	1. Deploy ability 2. Scalability 3. Self-actuation 4. Reconfigurability 5. Tunability 6. Easiness in manufacturing and assembly

1.5 Real-world examples of adaptable educational buildings and findings

As educational approaches and learning environments evolve, adaptable buildings have emerged as architectural marvels that accommodate shifting pedagogical approaches and dynamic learning environments. Around the globe, institutions have embraced the principles of flexibility, sustainability, and innovation to create cutting-edge educational spaces. Notable examples include the 'Eden Project Educational Center' in the United Kingdom, the 'Bendheim Integrative Learning Center' at Princeton University, and the 'Learning Resource Commons' at Humber College in Canada. These pioneering structures redefine adaptable learning and serve as models for 21st-century educational architecture."

Table 1.9 List of existing adaptable school design

Name	Location	Description
The Edge, Amsterdam, Netherlands	Amsterdam, Netherlands	The Edge is often cited as one of the worlds most sustainable and adaptable office buildings. Deloitte's headquarters in Amsterdam it features open-plan workspaces, meeting rooms with movable walls, and a variety of adaptable spaces for workshops and presentations. Its lighting, climate control, and workspace allocation are controlled through a smartphone app, allowing employees and students to customize their environment.
Stanford University Central Energy Facility	Stanford, California, USA	The Stanford Central Energy Facility is an adaptable building that houses energy production and campus utilities. It was designed with an innovative façade that adapts to temperature changes, helping to regulate building temperature passively. The facility's interior is modular and can be reconfigured to accommodate changing equipment and technology needs.

Mount Alexander College is a five-story, 4,590-square-meter secondary school on a compact inner-city campus. In addition to being equipped with administrative offices, junior science labs, and digital music technology facilities, the building emphasizes adaptability with flexible teaching and learning areas. Next to the vertical school building is a standalone canteen pavilion. Many stakeholders were involved in the project's development, including students, faculty, school council members, parents, and representatives of Wurundjeri Woi Wurrung Cultural Heritage Corporation. As a result of this collaboration, all parties were actively involved and supported throughout the project with spaces for technology, the arts, multimedia, and general teaching. The collaboration between all stakeholders ensured that the project had a comprehensive and holistic approach, considering the needs of all stakeholders. The final result is a facility tailored to the school and the local community's specific needs while respecting the area's cultural heritage. Notably, the ground floor encompasses performing and creative arts studios adjacent to an indoor breakout area, which doubles as an exhibition and gallery space for showcasing student artwork (Figure 1.21).

An expansive outdoor amphitheater on the ground level complements indoor performances, fully utilizing the facility's infrastructure, including advanced lighting and sound equipment. On the first level, administrative offices, staff common areas, reception spaces, and a spacious teaching area await, designed for easy conversion into an examination room when necessary. A connecting bridge from Wellington Street leads to an external walkway providing access to the new reception area and a balcony offering views of the campus. Transitioning to the second and third levels, one finds specialized junior science labs, dedicated visual and digital art spaces, robotics facilities, and materials technology learning zones, all surrounded by collaborative meeting rooms and a central breakout space.

The fourth level nurtures and supports senior VET (Vocational Education and Training) programs, mathematics, and English classes. These spaces seamlessly connect with an adjoining outdoor breakout area, which provides panoramic views of the city skyline. Moreover, the inner-city campus has an outdoor basketball half-court on the roof, providing a dynamic recreational component. Traditional owners carefully selected native plant species for the surrounding landscape and carefully planned to provide a variety of high-quality outdoor spaces. Building facades pay homage to the existing architectural character of the neighbourhood. Brick residential and civic structures. A contemporary reinterpretation of this heritage has precast red oxide concrete panels. A testament to the modern educational infrastructure, this adaptable educational building features flexible spaces, innovative design, and extensive stakeholder collaboration.

These real-world examples demonstrate how educational institutions and organizations have embraced adaptable design principles to create flexible, user-centric spaces that can evolve with changing needs and technologies. These buildings prioritize collaboration, technology integration, and sustainability while providing dynamic learning and working environments. For example, the Arizona State University's Polytechnic Campus features a learning commons with various flexible seating options, moveable walls, and a retractable ceiling, allowing the university to easily adjust the space to accommodate different learning styles and activities. Similarly, the University of South Florida's new library features an open layout with various seating options, glass walls, and the latest technology, creating an inviting and modern space (Figure 1.23).

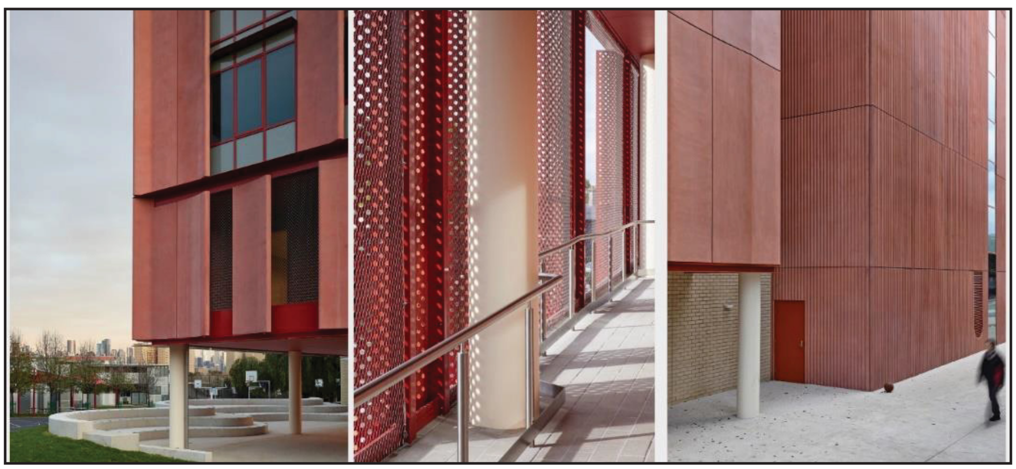


Figure 1.23 Facade pattern. Responsive façade
Source: https://kosloffarchitecture.com/project/mount-alexander-college/

Figure 1.24 Plans of the Arizona State University's Polytechnic
Source: https://kosloffarchitecture.com/project/mount-alexander-college/

In the context of this case study, one critical challenge is expanding space utilization. Effectively optimizing adaptable spaces without overloading them with congestion or leaving areas underutilized presents significant challenge.

1.6 Summary

Considering research problems in the construction industry, such as obsolescence, demolition, redundancy, waste of time, cost, and materials, DfAd is a solution. This literature review examines practical approaches and procedures to increase adaptability and flexibility. Furthermore, various building parts are identified based on open-building and layer-sharing approaches. Furthermore, this study demonstrates a methodological relationship between digital design, digital fabrication, and modularity, which are significant and valuable techniques. Also, modularity aids in extending the life of a building, improving its performance, and reducing the risk, time, and cost involved in its construction. Furthermore, using digital design facilitates the development of innovative solutions to problems. As a result of defining problems, constraints, and objectives as variables, parameters, and inputs, digital design provides solutions as outputs. Some digital techniques also incorporate the concept of modularity. As a result of the joint use of these concepts and strategies, achieving more adaptable and flexible design and simplifying the design process is possible.

CHAPTER 2

REASEARCH METHODOLOGY

2.1 Introduction

The purpose of this section is to describe the systematic approach employed to conduct this study. This section discusses how the researcher addressed the research questions, the data type, the sources and the data collection and analysis methods.

2.2 Design science research (DSR) methodology

The "research" refers to the process that contributes to understanding a phenomenon. A phenomenon is the behaviour of an object or system observed by a researcher or group of researchers. It is through "understanding" that one can predict specific characteristics of a phenomenon (Hevner & Chatterjee, 2010). In the context of designing, "engineering design" is an intelligent process for creating and evaluating artifacts based on their function and structure to achieve specified objectives and meet specified requirements and restrictions (Dym & Little, 2000, cited in (Hevner & Chatterjee, 2010). Table 2.1, provides some definitions for design science and design science research.

Table 2.1 Definition of design science and design science research

Authors	Years	Definition
Wieringa	2014	“Design science is the design and investigation of artifacts in context.”
Hevner & Chatterjee,	2010	“Design science research addresses important unsolved problems in unique or innovative ways or solved problems in more effective or efficient ways.”
Hevner & Chatterjee,	2010	“Design science research is motivated by the desire to improve the environment by introducing new and innovative artifacts and the processes for building these artifacts.”

Researchers can improve any design research project by understanding and recognizing the three phases of design science research (Figure 2.1). It is important to note that the "environment" includes participants in the form of people, organizational systems, and technological systems. Participants in this process define the requirements and indicators for evaluating the results. According to the "Relevance Cycle," the research environment serves as a context for the design of science research activities by recognizing the requirements as problems and opportunities.

The relevance cycle also includes answering the environmental question and evaluating the impact of the artifact. Field testing aids in evaluating the artifacts. The next phase of design science research involves designing artifacts and processes that the researcher should evaluate. According to Hevner & Chatterjee (2010), the design cycle is an internal activity. In this cycle of research activities, an artifact is repeatedly created, evaluated, and refined in response to feedback. As part of the Rigor Cycle, design science activities have a connection with the scientific background, experience, and expertise necessary to conduct the research project.

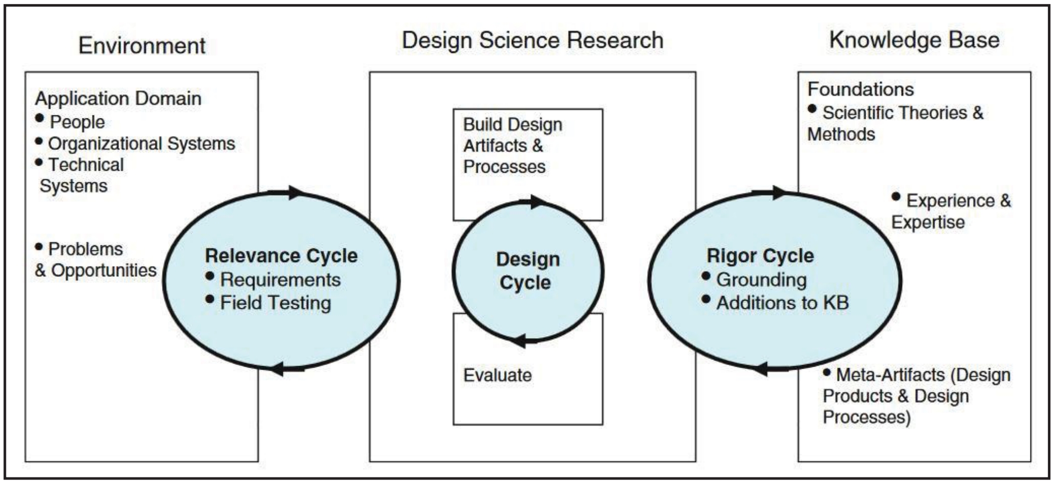


Figure 2.1 Design science research cycles
Taken from Hevner & Chatterjee (2010, p.16)

According to (Wieringa, 2014), the artifacts interact with the context. In addition, he stated that artifacts could be methods, techniques, and conceptual maps. Furthermore, context involves services, software, hardware, customers, and people. In the early stages of design science, the researcher should address two stages, namely, "design problems" and "knowledge questions." "Design problems" should be analyzed regarding users' objectives, whereas "knowledge questions" should not be based on users' intentions (Figure 2.2). By (Wieringa, 2014), design science research relies on a framework. In this framework, "stakeholders" have roles in designing artifacts by providing financial grants and determining the objectives and "knowledge" that assist in their development (De Sordi, 2021). The stakeholders include users, customers, designers, manufacturers, and machinists. In this framework, designing artifacts to solve problems is integrated with answering knowledge questions to investigate the impact of artifacts on context.

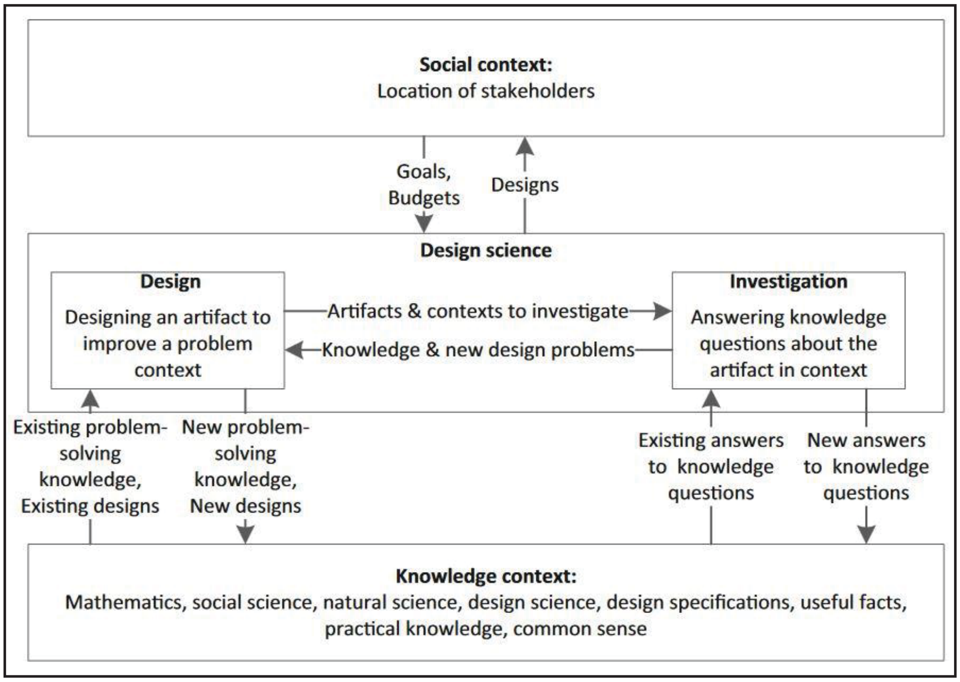


Figure 2.2 A framework for design science research
Taken from Wieringa (2014, p.7)

Using DSR, one can investigate the research context, context problems, requirements, knowledge questions, valuable facts, and expected artifacts. The real world problem addressed in this research is related to the fact that a considerable amount of demolition and waste of materials and resources is associated with deconstructing building components. In addition, conventional building components cannot be converted and scalable. Changing monofunctional spaces into multifunctional spaces requires excellent flexibility in layers and components. In light of the literature review, the "close loop" and the "slow loop" are two of the most critical concepts in CE. Through these two concepts, it is possible to increase the life cycle of a building and reuse materials and resources. Based on the literature review, some strategies can help increase the flexibility and adaptability of buildings to respond to changes and achieve circular economy and sustainability. Three facts are important: modularity, digital design, and digital fabrication. As a result, each factor impacts the design, production, and supply chain processes to enhance a product's adaptability level. In addition, these facts contribute to improving the context's problem and achieving the context's objectives. This report begins with a description of the overall design problems and questions. Generating an adaptive plan, services, and façade through modularity is critical to generating artifacts. The provided scheme (Figure 2.3) outlines the systematic approach to spatial design, beginning with identifying problems related to space functionality and services. The process iteratively refines the design through a series of evaluations and revisions. Initially, the problems are defined, which include spaces with a single function, rigid spatial connections, and a lack of sufficient services. A candidate method is then selected to guide the initial design, considering the spatial plan and service integration. Key variables and requirements are focusing on the flexibility and adaptability of spaces. Variables such as orientation, adjacency, and accessibility are identified, along with the need for spaces that can change function, have detachable connections, and provide excess capacity for services.

These samples are subjected to an initial evaluation to assess their effectiveness in solving the identified problems and meeting the design requirements. Based on the outcomes of the first evaluation, it is possible to decide on the best design sample. This chosen design is then put through a second evaluation to confirm its suitability. If the design does not meet the desired criteria during the second evaluation, it is sent back for re-evaluation, indicating a recursive improvement process. After successfully passing the second evaluation, the design is suitable candidate for implementation, having met the necessary criteria for functionality, adaptability, and service provision within the space. This iterative process ensures that the final design is well-considered and tailored to effectively address the initial spatial challenges.

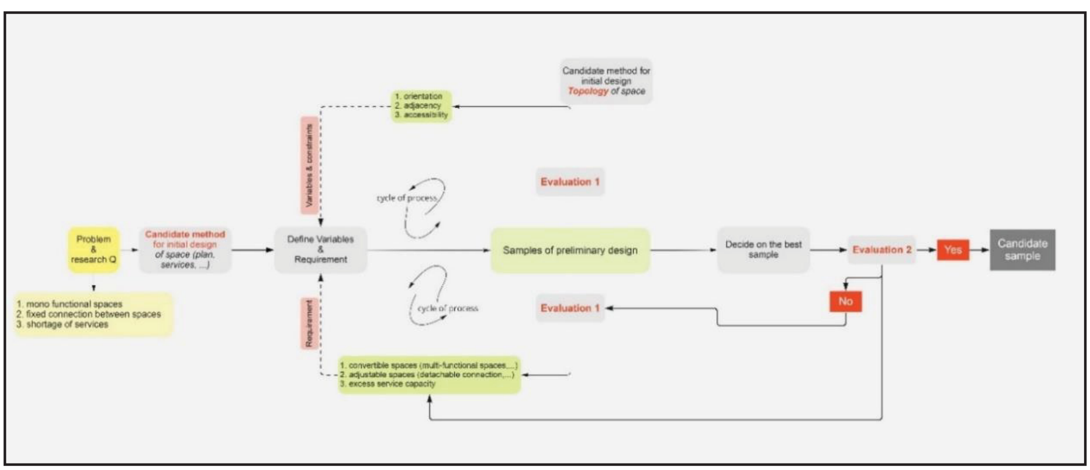


Figure 2.3 Systematic approach to spatial design

Figure 2.4 illustrates comprehensive information on the research project based on a literature review. According to the scheme, there are two main gaps:

- The gap between conceptual design and actual operation indicates a disconnection between initial design ideas and their implementation in practice. It is common in design and construction for a concept to appear feasible on paper or in digital models, but unforeseen challenges may arise regarding actual implementation. There may be technical limitations, cost overruns, or logistical issues not anticipated at the conceptual stage. This top-down approach ensures that the conceptual design is grounded in practical assembly considerations, smoother the transition to actual operation.
    - Testing design on a small scale: The second gap points to the need for testing design on a smaller scale to catch and rectify errors before the total production or construction. This step is crucial because changing a small-scale model or prototype is more cost-effective and less risky than altering a large-scale project after the quality control. Solution - Defining mechanisms for moving vertical and horizontal surfaces (bottom-up view): The solution proposed here involves a bottom-up approach, which starts at the most detailed level of the design and works upwards. It might involve defining mechanisms to move vertical and horizontal surfaces in this context. The strategy of mono-functional spaces is to transform them into multi-purpose ones, ensuring that the design's individual components are functional and adaptable before being incorporated into the more extensive system.

In summary, implementing these two solutions can address the critical challenges of ensuring designs are both feasible in practice. In addition, designs can be flexible enough to adapt to changing needs or identify errors early in the process. The solutions represent a strategic blend of top-down and bottom-up views in design thinking, promoting a more integrated and holistic approach to design and its implementation. The changes in four categories, ‘aesthetic upgrade, functional, spatial and technical upgrade, ' are shown in the scheme. Also, there are two main problems: ‘obsolete and redundancy.’ The building can be classified through shearing layers and includes ‘site, skin, structure, space plan, services and stuff.’

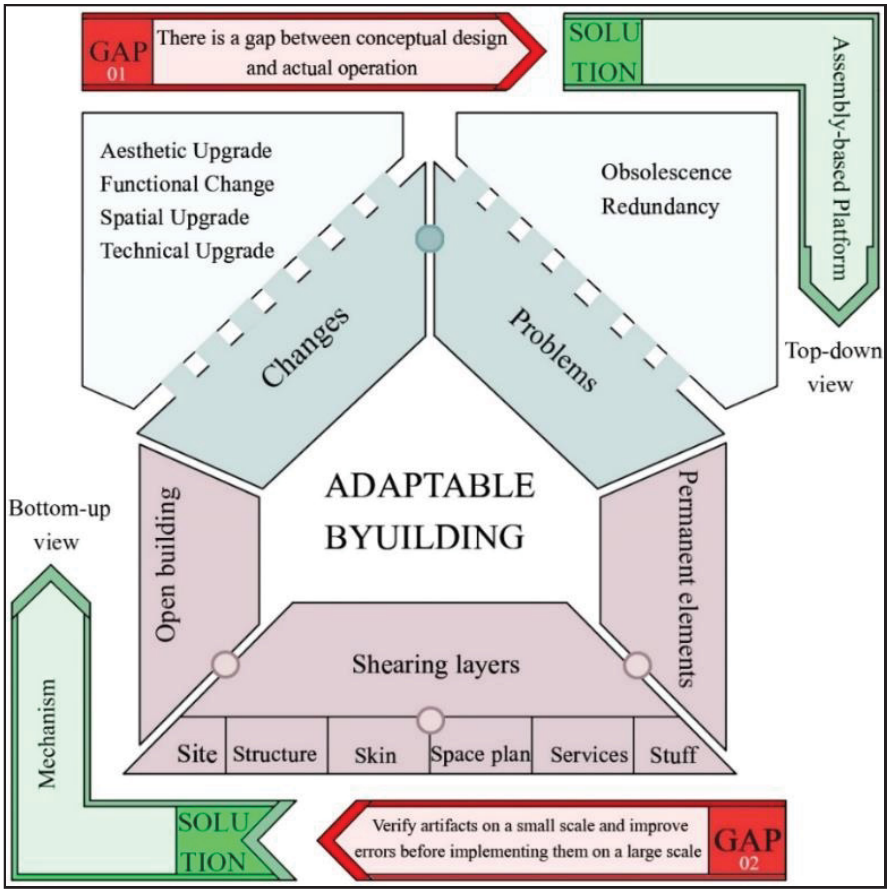


Figure 2.4 Comprehensive information of
Research project based on literature review

2.2.1 Identify enablers, variables (mediator, moderator & control)

In the research of Askar et al. (2021), several independent variables, qualitative or quantitative, were identified as capable to increase a building's adaptability level. Furthermore, the mediator, moderator, and control variables were found to have functional relationships to optimize and ease the process of attaining the aim and objectives of this study. The variables are as follows:

- Six leading indicators of adaptability are considered independent variables: "movable, convertible, adjustable, scalable, versatile, and refittable".
- Dependent variables: Levels of adaptability and flexibility (LoA) are dependent variables. According to the literature review, there are six layers of a building, known as shearing layers, and three levels of open buildings.

These variables are control, moderator, and mediator (Figure 2.5):

- Control variables: Digital fabrication
- Moderator variables: Digital design
- Mediator variables: Modularity, DfMA

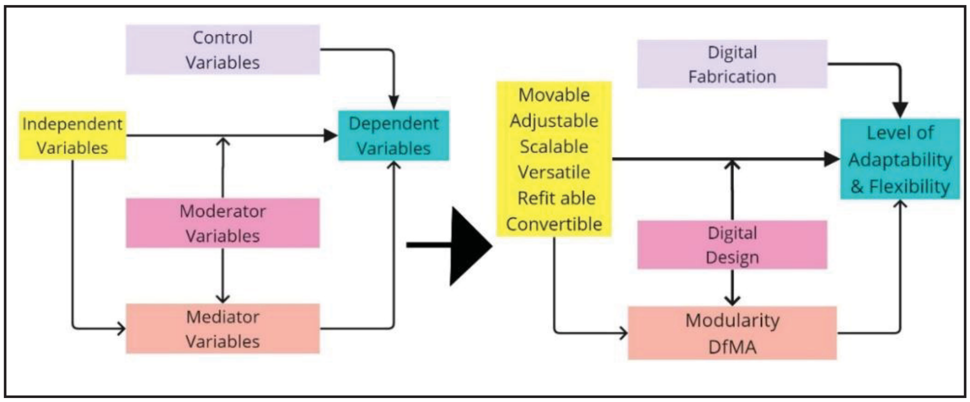


Figure 2.5 Connection of different themes of the project

Based on six adaptability indicators, the adaptability level involves the function, performance, space, size, task, and location factors (Figure 2.6). These indicators help the system's ability to serve various purposes, maintain effectiveness under different conditions, modify its layout, expand or contract as needed, support different activities, and operate in various environments. Together, these factors provide a comprehensive view of the system's flexibility and responsiveness to changing requirements and conditions. Adaptability in space means the design can be rearranged or restructured to accommodate different uses or needs. Figure 2.6, shows how each adaptability characteristic (independent variable) impacts specific aspects of a building's adaptability (dependent variable). For instance, convertibility influences the adaptability in function, while scalability affects adaptability in size. This visual representation helps understand how different features contribute to the overall adaptability of the system or structure, enhancing its ability to meet various requirements and conditions effectively.

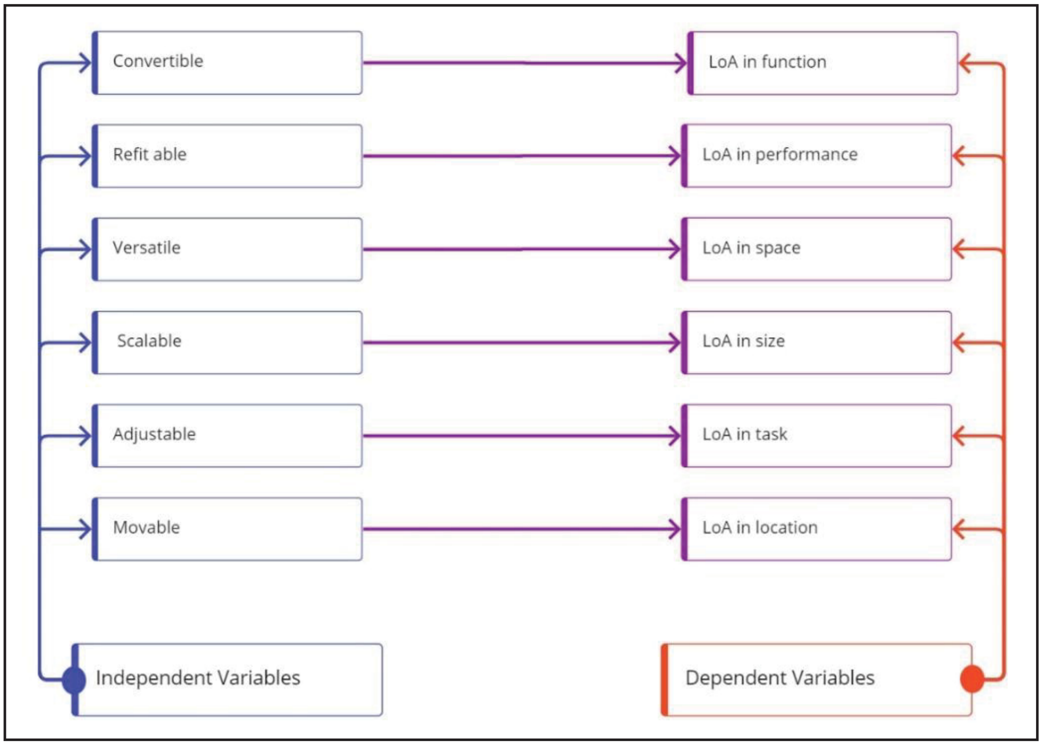


Figure 2.6 General relationships between different
Variables of the research
Taken from Askar et al. (2021)

The following scheme (Figure 2.7) illustrates the role of indicators of adaptability in different shearing layers (Anupa Manewa1 et al. 2013).

- Convertible: in services, structure, spaces
- Refi-table: in site, services, structure
- Versatile: in services, skin, space
- Scalable: in stuff, skin, structure, space
- Adjustable: in skin, stuff, space
- Movable: in space, skin, structure, staff

This study highlights the importance of designing buildings that can easily adapt to changing needs and conditions, ensuring long-term usability and resource efficiency. This approach not only addresses current challenges in the construction industry but also sets a foundation for future developments in adaptable building design.

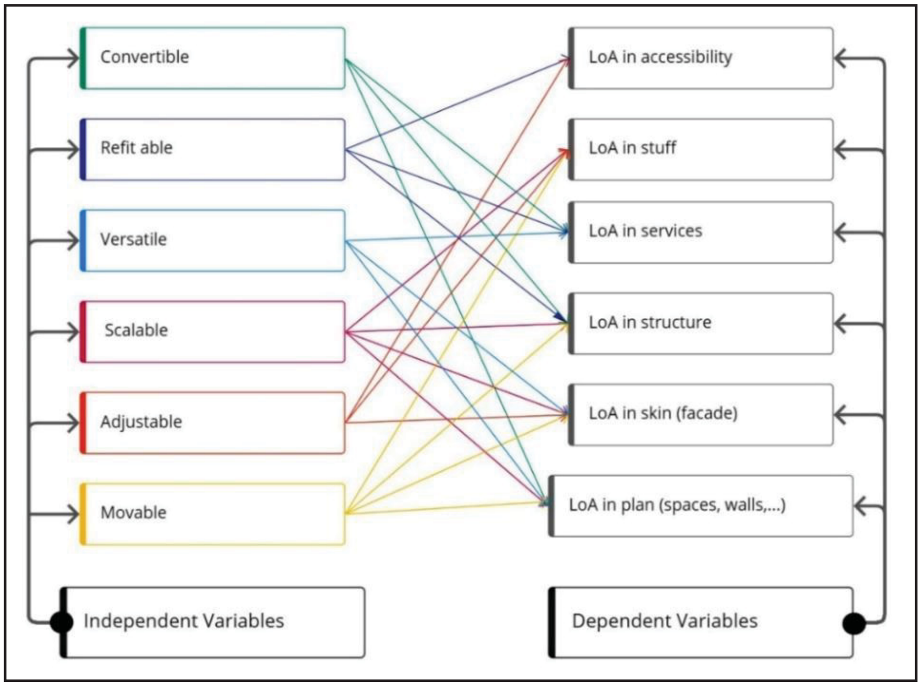


Figure 2.7 Relation between indicators of adaptability
& level of adaptability in shearing layers of the building

2.2.2 Identify connections between enablers and variables

The following scheme indicates the relations between different variables. The following scheme illustrates the impact of each variable on the other variables. For example, in digital design, as moderator variable, interlocking blocks integrate with the modularity concept (Figure 2.8). These elements have independent specifications. There is similarity between the structure of production and the design process. Modular products allow components to be replaced. Also, by implementing DfMA principles in independent variables, the level of adaptability in different building layers will be increased.

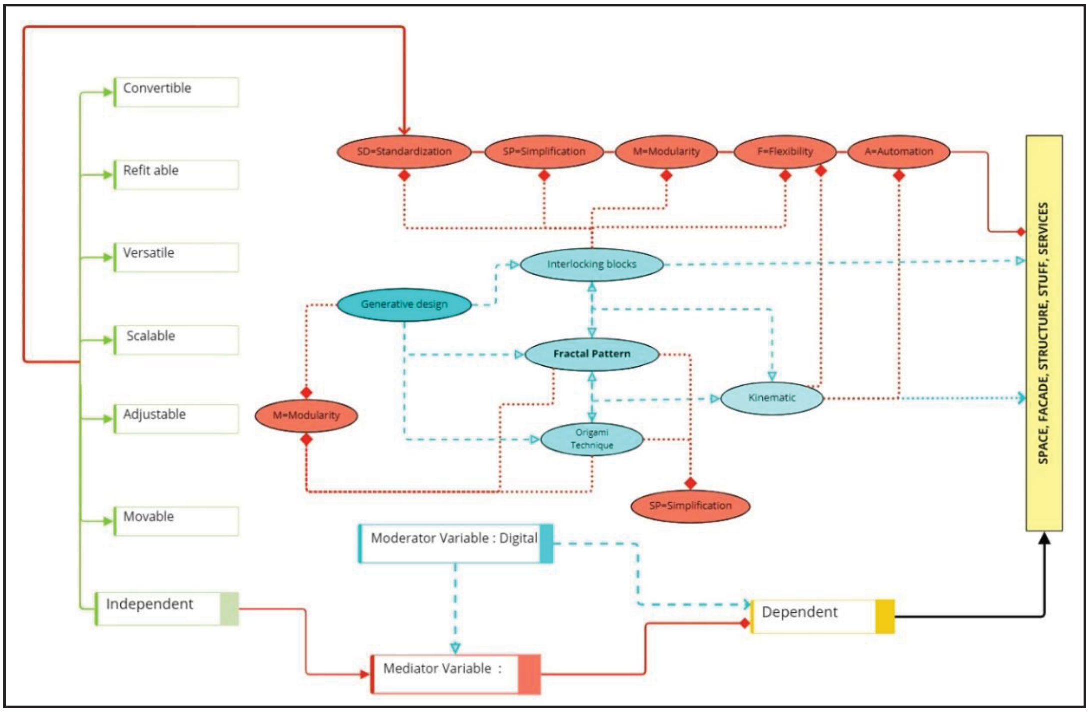


Figure 2.8 The relation of IN & D variables, based on DfMA principles

In the following scheme (Figure 2.9), three central perspectives of DfMA, automation, flexibility and standardization, aid in increasing the productivity of kinematics. It aids in reducing manual force and the time required for assembly and disassembly.

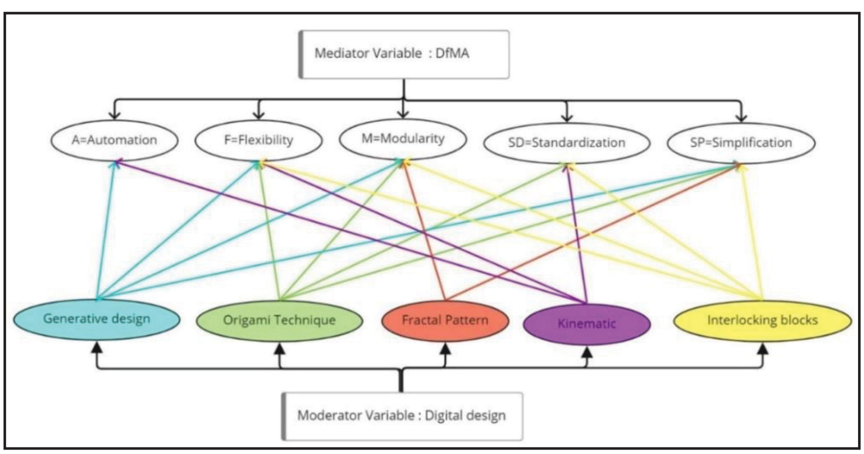


Figure 2.9 The relations of mediator variable (DfMA)
& moderator variable (digital design)

The following scheme (Figure 2.10) indicates the impact of the moderator variable on the mediator variable. It shows that generative design can affect the modularity of products and processes. Also, origami techniques can streamline product, process and supply chain complexity. In addition, the fractal pattern is beneficial in achieving modularity concepts in products and processes. The kinematic aids in simplifying the modularity of the product, process, and supply chain.

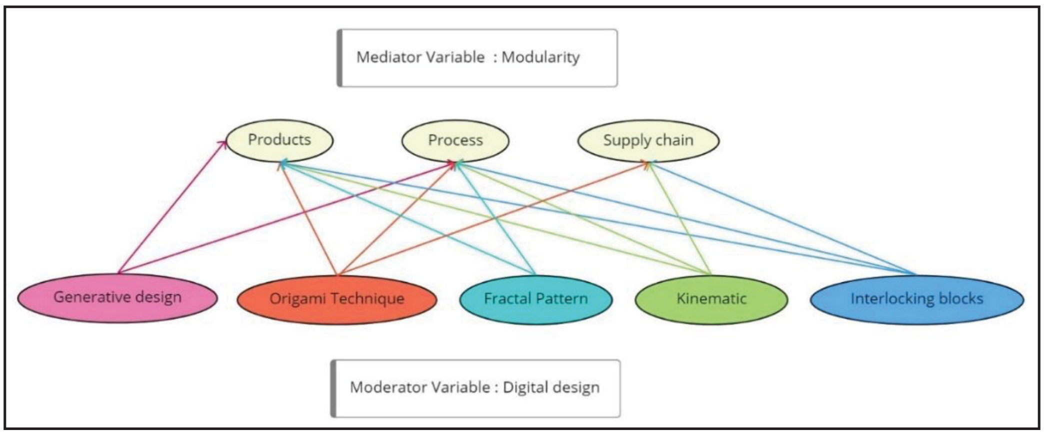


Figure 2.10 The relations of mediator variable (modularity) & moderator variable (digital design)

2.2.3 Problem statement

According to Askar et al. 2021, the idea of adaptable and flexible buildings has always been prominent when it comes to dealing with building "obsolescence" and "redundancy." So, users' requirements and social contexts change, and buildings become obsolete. Askar et al. (2021). The present Master's thesis research aims to contribute to the solution of this problem.

2.2.4 Research questions

The research questions guiding the explorations are as follows:

1. How does the adaptability of buildings contribute to addressing changes during the lifecycle of a building?

2. How can generative design (as part of digital design) be incorporated into an adaptable and flexible building?
3. How can digital design help producing innovative design solutions, increasing flexibility and adaptability?
4. How can Modularity & Digital Design be applied to design for adaptability?

2.2.5 Aim and objectives

The overall aim of this research is:

- Enhance the level of flexibility and adaptability of buildings through modularity, DfMA, digital design and digital fabrication.

The objectives of the study are:

- ❑ Create a framework of modularity, digital design and fabrication as enablers for adaptable buildings.
- ❑ Design and fabricate enablers for demountable parts of buildings.
- ❑ Partial implementation of framework on a real-world project.

2.2.6 The roadmap of design science research methodology

Based on the literature on DSR, we identify four main steps to d a primary conceptual framework (Figure 2.11).

- Step 1: Initial identification of the research project
- Step 2: Development and identification of the research project
- Step 3: Initial theoretical design of conceptual frameworks for adaptability
- Step 4: Evaluation & Application of the conceptual frameworks for adaptability

These are the steps we are following in the next chapters, unfolding the Master’s research.

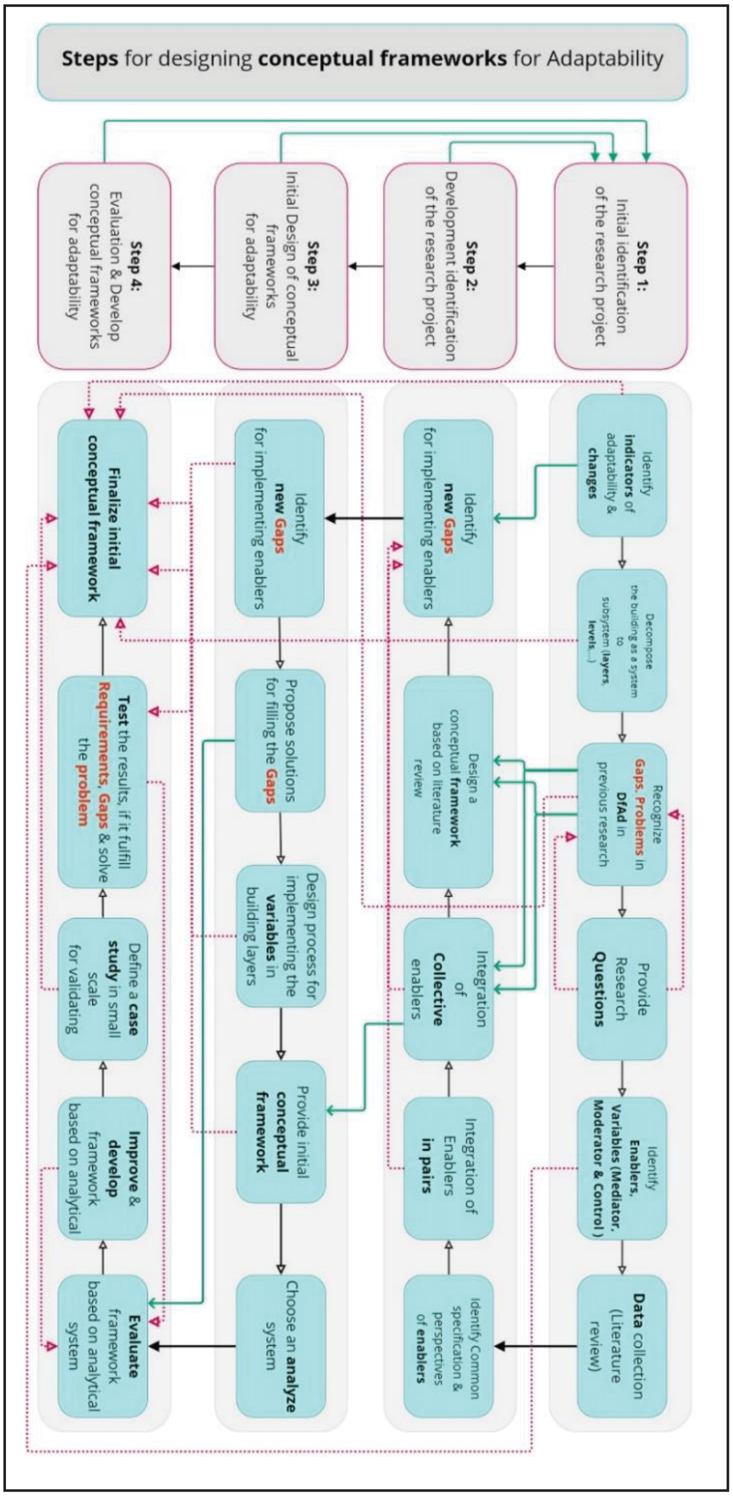


Figure 2.11 Steps for designing conceptual Frameworks for Adaptability

The stages of development of the application of the theoretical framework on a real-world project, based on the DSR method, are presented on Figure 2.12.

1. Define an assembly-based guideline.
2. Analyze the guidelines and design a mechanism
3. Build a prototype
4. Evaluate and validate the artifacts

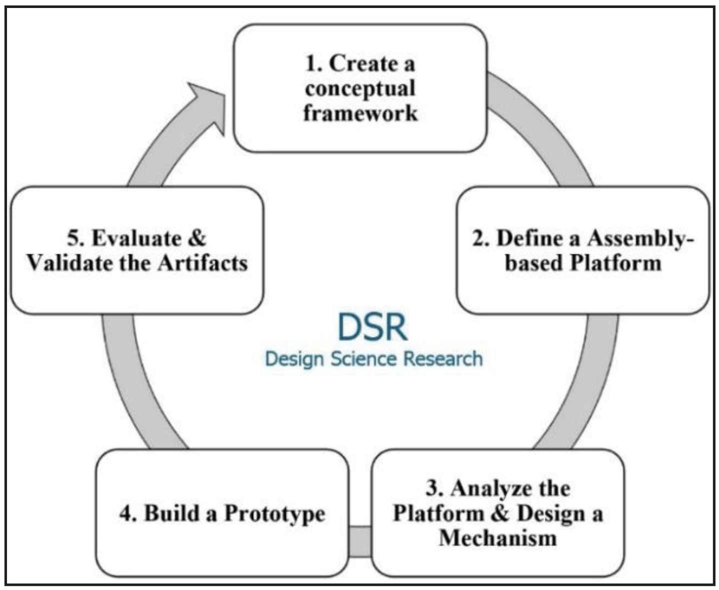


Figure 2.12 The DSR methodology for designing an adaptable building

Initially, the chapters outline the creation of a conceptual framework, providing the theoretical foundation and research context. The subsequent chapters analyze and designing specific mechanisms that align with the overall framework. Prototyping is then explored, describing the development and testing of initial models. Finally, the chapters evaluate and validate the artifacts, using empirical methods to assess their effectiveness and refine the design. This iterative process ensures a comprehensive approach to research and development, aligning each chapter with a specific DSR phase to systematically address the study’s objectives.

2.3 Summary

Figure 2.13, summarized the results of the literature review. The circle on the outside of the graphic indicates the six adaptability indicators. In the second circle, the modularity aspects are indicated, namely product, process and supply chain. The principles of DfMA are in the next circle: simplification, standardization, flexibility and automation. Generative design, Interlocking blocks and Kinematics are modularity approaches. Robotic arms and Arduino enable precise and efficient fabrication, facilitating the rapid iteration and testing of design concepts.

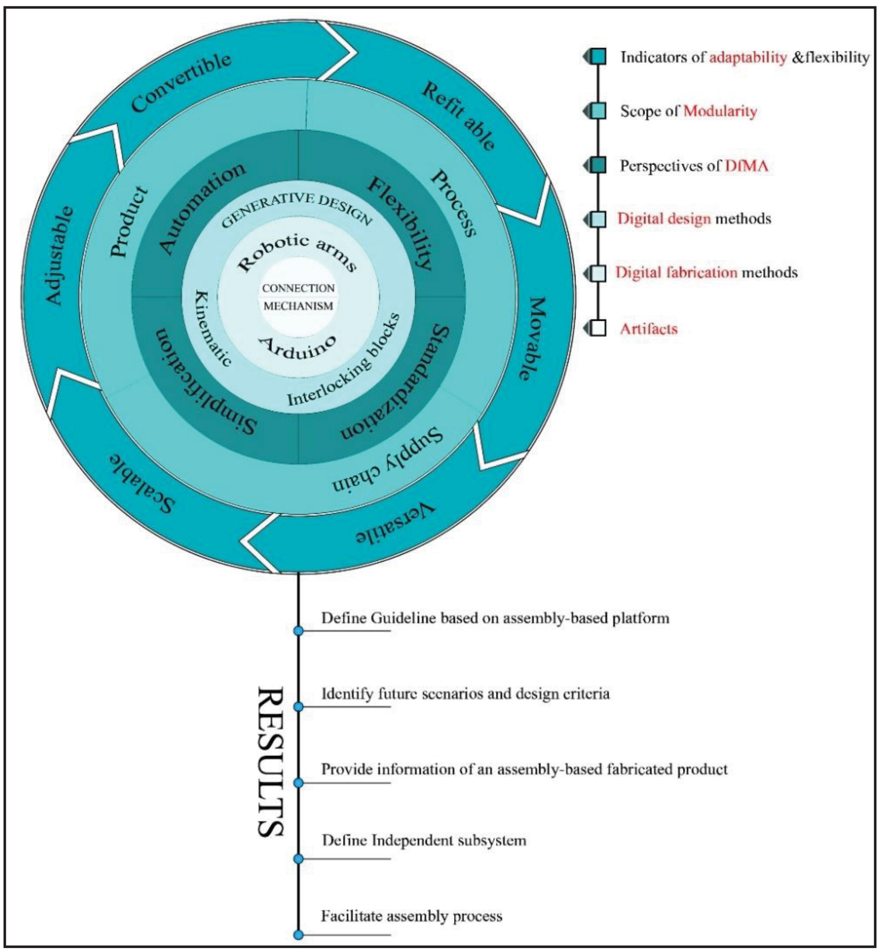


Figure 2.13 Graphical summary of the literature review - Initial stage of the DSR method

In the following chapter, the first iteration of the proposed theoretical framework is presented.

CHAPTER 3

A CONCEPTUAL FRAMEWORK FOR DESIGNING FOR ADAPTABILITY BASED ON MODULARITY, DfMA, DIGITAL DESIGN AND FABRICATION

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Abstract

Many issues arise from inefficient construction methods, including health hazards, increased costs, time waste, and substandard quality. The circular economy (CE) concept and design for adaptability (DfAd) are both practical long-term strategies to address obsolete and ineffective construction practices and increase usability, efficiency, and cost-effectiveness. Designing for circularity through adaptability is more sustainable and environmentally friendly, enabling the user to extend the building's lifespan and respond to the changes. This study uses Design Science Research methodology to leverage the role of modularity through digital design and fabrication based on DfMA principles. This paper proposes a conceptual framework that outlines a systematic approach to designing an adaptable building system drawing on insights from previous research. It emphasizes the importance of collaboration between designers, engineers, fabricators, and other stakeholders to enable rapid prototyping, iteration, and customization. The present research consists of four steps, beginning with exploring current approaches and procedures for analyzing adaptable buildings. In the second step, a systematic literature review identifies and illustrates the roles and relations of different adaptability enablers using MAXQDA as a qualitative data analysis tool to code and analyze scientific papers. The findings support the idea of complementarity between modularization, on the one hand, and digital design and fabrication, on the other, in adapting to low and high-frequency changes, increasing the adaptability and flexibility of buildings. As a concluding point, the

proposed conceptual framework has the potential to bridge DfAd enablers and customer requirements, ensuring that the design solutions meet the customers' needs.

Keywords: Digital Fabrication, Digital Design, Adaptability, Circular Economy, Modularity, DfMA, DfAd

3.1 Introduction

Building construction impacts the environment by using energy and resources and generating waste materials. Additionally, traditional construction methods are often inefficient, thus provoking issues such as safety hazards, high costs, poor environmental conditions, and low quality. To address these issues, designing adaptable and flexible buildings has become a significant research subject, potentially providing a sustainable solution for outdated and poorly functioning buildings. CE is "the dynamic total of associated processes, materials, and stakeholders that accommodate circular flows of building materials and products at optimal rates and utilities." (Geldermans et al. 2019). In the scope of construction, and context of the architectural aspect, according to (Klinge et al., 2019), an adaptable building is valuable for CE to decrease waste materials. They stated that design for adaptability is an enabler for achieving ‘CE’ and could deal with two issues of "obsolescence" and "redundancy" in the building.

Concerning this purpose, DfAd aids in increasing the lifespan of the different building parts and components. Also, DfAd contributes to CE to reduce resource and energy consumption to minimize the impact of construction on the environment. (European Environment Agency, 2017) addressed two "closing loop" and "slowing loop" strategies in CE. For the "closing loop," the features of recycling and reusing the materials and components should be addressed. In addition, for a "slowing loop," the features of extending the lifespan of the building need to be considered (Askar et al., 2021). Circular economies aim to minimize waste and increase the duration of resources. As the term implies, adaptability refers to the ability of a building or system to change and respond to changing needs or circumstances (Ross et al., 2016). Modularity as a helpful concept significantly impacts the product, process, and supply chain (Lennartsson & Björnfot, 2010). Also, modularity can decompose a building from system to subsystem (Rodrigues et al., 2014). Also, it can increase standardized components and interfaces and reduce the time and cost of reusing, maintaining, and retrofitting building elements (Viana et al., 2017). In the environmental and construction phases, modular prefabricated buildings reduce waste materials and time, recycling, and adaptability to the elements (Minunno et al., 2018). The aim of modularity is applicable to achieve standardization through material, component, and [8] connection (Viana et al., 2017). In addition, shearing layers refer to the different layers of a building that change or evolve at different rates over time. Buildings can be designed to accommodate changes in each layer. Architects and builders can create more adaptable and flexible buildings over time by understanding and designing for shearing layers. This research proposes a conceptual framework incorporating modularity, digital design, and fabrication to enable adaptable buildings and to partially implement this framework on a BPMN (business process mapping notation). The study utilizes the Design Science Research methodology to propose conceptual framework incorporating modularity, digital design, and fabrication to enable adaptable buildings. In this study, the relevant literature is reviewed, data collection and analysis methods are employed, and results are analyzed and discussed, along with implementing the conceptual framework in BPMN processes. Key findings are summarized, and future research areas are suggested based on the study results.

3.2 Literature review – main concepts and theories

Literature reviews provide an overview of current knowledge in the field and serve as a starting point for this research. This section defines key concepts relevant to the research, including adaptability and flexibility. Additionally, this chapter discusses the types of changes to a building's physical structure over time and changes to its intended use. It indicates the frequently used theory of the shearing layers – as a foundation for adaptability.

3.2.1 Adaptability and flexibility

The design of today's building systems is challenging due to their complexity, unpredictability, rapid technological advancements or technological obsolescence. Flexibility is characterized by rapid, short-term, and frequent changes, which indicate the ability of a system to adapt to changes in its environment. Adaptability, however, refers to low-frequency alterations over a prolonged period. Nakib (2010) proposes several levels of building adaptability and flexibility (Nakib, 2010). Users can adapt a building to meet their specific needs, improve their comfort and security, and strengthen their connections to the building and other users. Also, adapting is essential for fulfilling individual and social needs (Ismail & Rahim, 2011). Various factors help enhance flexibility and adaptability in building construction. These factors include the size and dimension of components and layers, their position, task, performance, function, type, scale, and the extent of the spaces (Manewa et al., 2016). These factors are movable, adjustable, scalable, versatile, refit able and convertible. Using movable features in building design promotes adaptability and reduces the need for demolition by enabling the reuse of walls through easy connections and disassembly. Additionally, incorporating prefabricated and modular movable elements can facilitate the resizing or extension of spaces, allowing for greater flexibility in building design.

3.2.2 Changes in the building

There are several types of factors provoking changes over the lifespan of a building. Designing for adaptability and flexibility improves the building's ability to adapt to changes and increases the life span of the components (Askar et al., 2021). These changes occur for several reasons. Over the years, individual demands have increased due to limitations in the availability of suitable spaces, the high number of vacant spaces and changes in the function of the building. The type of changes in customer demands varies over the life of a building for several reasons, according to Dobbelsteen, 2004 cited in (Ismail & Rahim, 2011). According to (Sadafi et al., 2014), there have been two significant changes to the interior and exterior parts of the building over time. Buildings are affected by both internal and external factors. Buildings undergo internal factors such as function, performance, and aesthetic changes. External factors include environmental changes, such as climate changes and technological advancements, such as applying innovative technologies.

3.2.3 Shearing layers

A building is a system with different subsystems. These subsystems contain shearing layers with different lifespans (Estaji, 2017). As per Estaji's classification (2017), a building has six different layers: site, structure, skin, services, space plan and stuff. The "site" layer refers to the building's location, surroundings, and orientation, while the "skin" layer consists of exterior walls and façade. The "structure" layer includes the foundation, columns, and load-bearing elements, while the "services" layer includes the vertical and horizontal pipes used for mechanical and electrical purposes in the building. The "space plan" layer refers to the interior layout and elements of the building, and the "stuff" layer refers to the furniture and appliances within the building. Each layer has a different lifespan, from everyday alterations to over 300 years (Anupa Manewa et al., 2013). Therefore, building design should incorporate flexibility for short-term changes and adaptability for long-term changes. Thus, this literature review suggests that building design should be oriented towards adaptability and flexibility to meet changing demands and increase the life of components.

3.3 Methodology

This article uses a Design Science Research methodology to propose a conceptual framework based on modularity and digital techniques, aiming at design for adaptability in different building layers. As a potential contribution to architecture and construction, the proposed framework would facilitate the development of more resilient, adaptive, and sustainable built environments. Future research can continue to validate and refine its implementation in practice. A qualitative data analysis tool, MAXQDA, analyzes scientific literature.

3.4 Literature review – analysis

This section delves into the comprehensive analysis of the existing literature concerning the integration of DfMA and modularity in architectural practices.

3.4.1 Systematic literature review

A systematic literature review involves identifying and assessing relevant articles on specific issues and the scope of the research (Kitchenham, 2004). According to Cochrane Collaboration, 2014 cited in (Siddaway et al., 2019), systematic reviews have numerous advantages, such as in-depth topic analysis. Using search keywords such as "adaptability and flexibility," "modularity," and "digital design, "DfMA," adaptability principles and indicators were searched for through publications from 2010 to 2021. After filtering the 450 articles (result from the search on Scopus, Web of Science, Elsevier, and Research Gate), 100 were retained and coded in the MAXQDA software. Conducting such analyses is meant to facilitate understanding the relations between these themes. It can also aid in identifying areas where more in-depth analysis or further research may be needed. In MAXQDA, a code map visualizes the relationships between codes and identifies patterns in the data map Figure 3.1, presents a network diagram illustrating the relationships between the different codes.

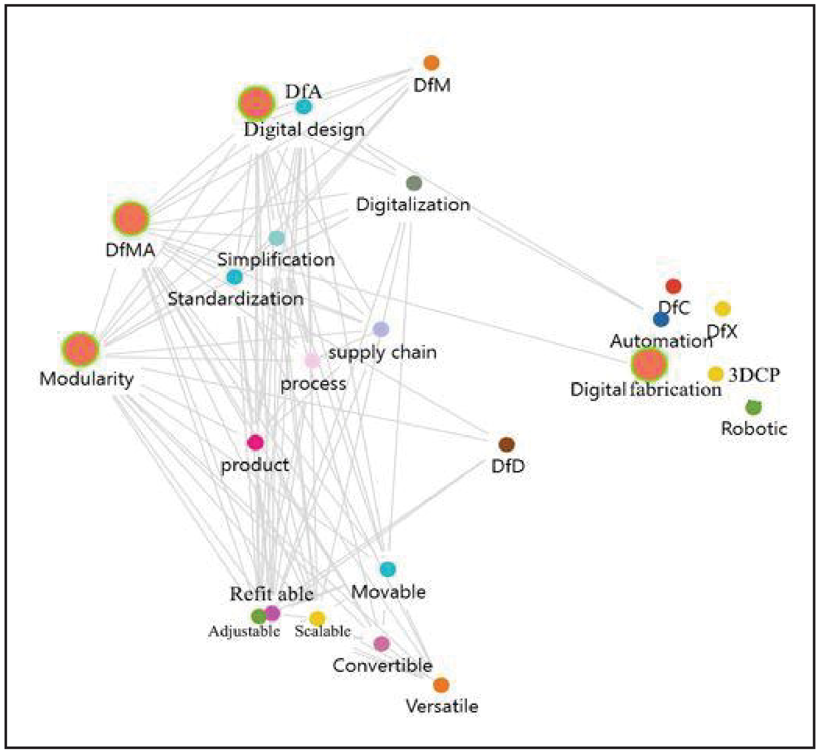

Figure 3.1 Code maps in MAXQDA
the pattern of relations between different variables

The following schemes (Figure 3.2) illustrate the comparison of segments coded with three codes: DfMA, Modularity, and Adaptability indicators (as per 150 articles). Approximately 800 segments include coded in the relevant articles on DfMA, adaptable building, modularity, and digitalization. About 59 percent of articles refer to DfMA principles. In addition, based on coded segments, 41 percent of respondents use the modularity concept. The coding showed that among the 'adaptability indicators' in the articles on adaptable building, 'scalability,' with 25%, has the highest frequency. However, 'movable' has the lowest consideration, suggesting further research is needed.

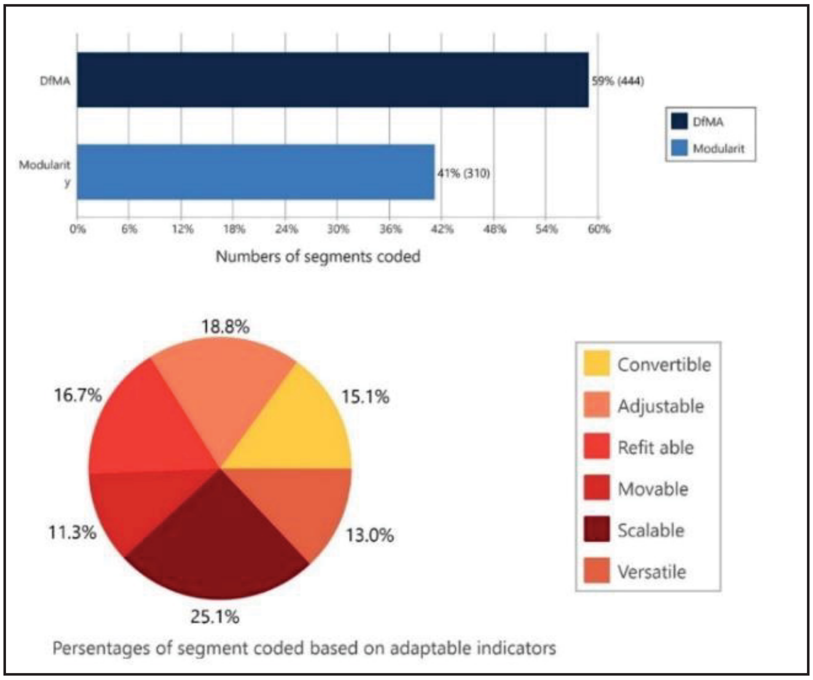

Figure 3.2 Code frequencies
(Documents and segments with codes) in MAXQDA

Figure 3.3, illustrates the percentage distribution of document codes based on an analysis of code frequencies in MAXQDA. Through the four themes of 'modularity,' 'DfMA,' 'digitalization,' and 'adaptability,' some comparisons are presented among all documents. The design concept for assembly (DfA) in DfMA is more closely related to adaptability indicators. The principle of 'standardization' in DfMA is more strongly associated with the concept of adaptability indicators. It is more common to use digital design in designing for adaptability, but more use of DfAB (digital fabrication) is needed. In designing for adaptability, "adjustable" and "scalable" can contribute more. In addition, the' DfM' concept needs more consideration.

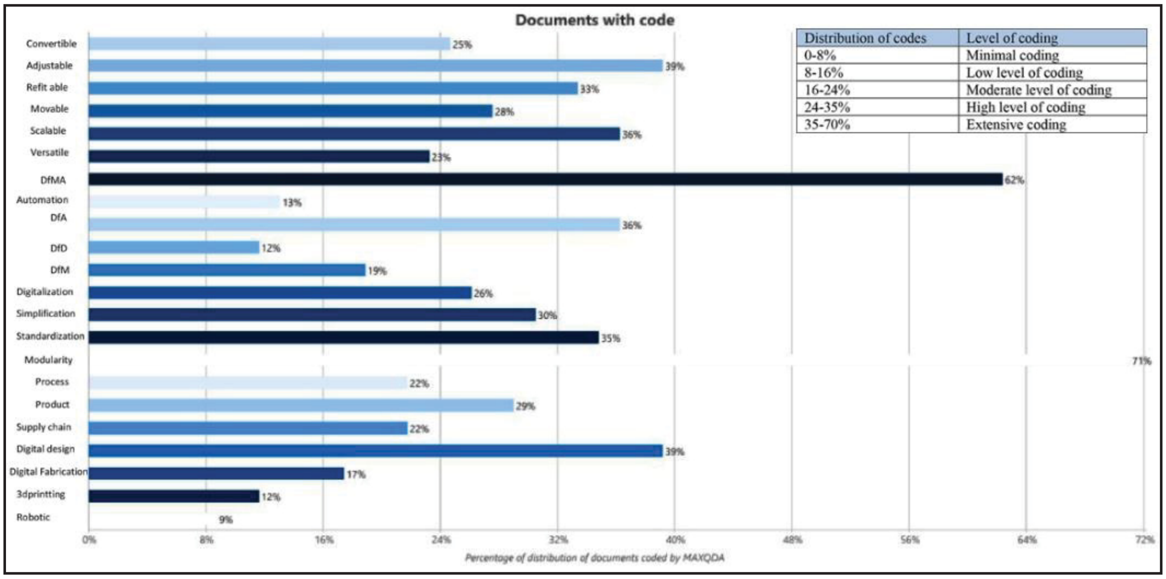

Figure 3.3 Percentages of distribution of document codes by analyzing code frequencies in MAXQDA

3.4.2 Integrating modularity, digital fabrication, digital design and DfMA

According to (Ismail & Rahim, 2011), it is possible to streamline the design and construction process by integrating digitalization with modularity when designing adaptable buildings to make the process more flexible and efficient. Architects and engineers can create 2D and 3D models of buildings and their components using computer-aided tools such as Building Information Modeling (BIM) or Grasshopper (Cavalliere et al., 2019). The following diagram indicates the relationship between the different variables as an initial process for the analysis in MAXQDA (Figure 3.4).

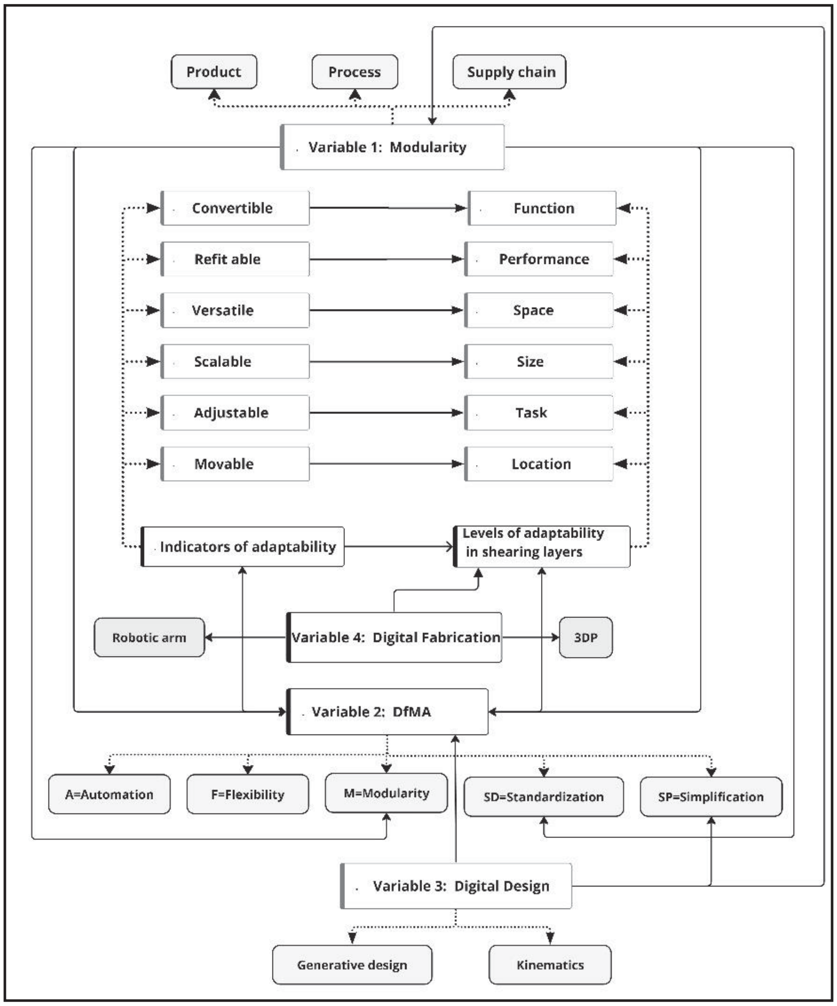

Figure 3.4 Integrating modularity, digital fabrication, digital design and DfMA for adaptable buildings

There are several ways to apply modularity and digital design to design for adaptability: modularity allows building components for assembly, disassembly, and reconfiguring quickly. 3DP and robotics aid in the manufacture of modular building components quickly and efficiently, allowing rapid construction and reconfiguration (Graser et al., 2021). Offsite construction (OSC) buildings can benefit from the digital fabrication process in several ways: Precision: with Dfab, building components can be precisely fabricated and assembled on-site according to exact specifications (Vazquez & Jabi, 2015). Customization: Using Dfab, building components can be customized to meet specific project requirements while maintaining modularity (Tessmann & Rossi, 2019). Efficiency: Dfab increases efficiency by reducing production costs and time (Afsari, 2018). Quality control: Dfab ensures consistent quality control throughout manufacturing, reducing errors and ensuring all components meet requirements (Akinradewo et al., 2021). Kinematics is concerned with the causes and effects of motion (Moloney, 2011). As part of adaptable building design, kinematics aids in designing building components and systems capable of moving or changing positions in response to changing conditions. Using movable walls or partitions is an example of kinematic design in adaptable buildings. Such movable walls include built-in mechanisms facilitating easy movement and positioning (Ayyappan & Kumari, 2018). In addition to enabling adaptable building components, kinematic design has the potential to create shading devices, louvres or blinds that can be adjusted (Moloney, 2011).

3.5 Conceptual framework

Based on the literature review and the outcomes from the coding analysis, this research proposes a conceptual framework for building adaptability based on modularity and DfMA. As a further step, a potential operationalization of the framework includes a scheme.

3.5.1 Definition of the conceptual framework

A conceptual framework for adaptable buildings is a theoretical approach to building design and construction (Figure 3.5). Considering future changes to the building's function, occupancy, and technology involves designing systems, spaces, and components that can be easily modified, added to, or reconfigured to meet future requirements. The following key concepts form the framework: DfMA principles: Flexibility, automation, simplification, modularity, and digitalization. Manufacturing building components offsite allows for improved quality control, reduced site waste, and faster construction times (Tan et al., 2020a). Modularity: Using standardized and modular components that can be reconfigured by contractors or users, added to, or replaced in response to changes in the building's use, occupancy, or technology. Using standardized, repeatable components and systems allows for economies of scale and reduces design and construction time. Occupant-centred design: The consideration of user needs and preferences in the design process to ensure that the building and its permanent elements meet the needs and expectations of its occupants (Baranauskas, 2019).

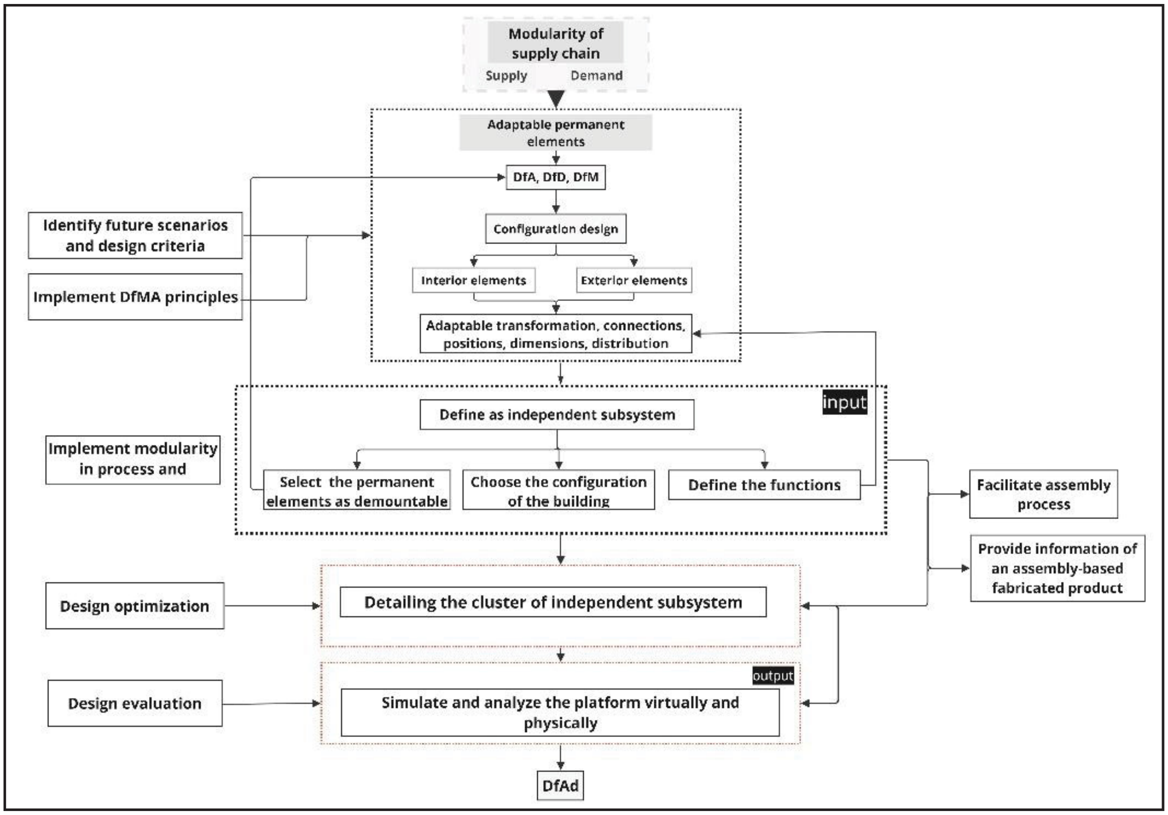

Figure 3.5 Conceptual framework for DfMA through Modularity

By incorporating these principles into the digital design and manufacturing process, the conceptual framework for modularity and DfMA aims to create a more sustainable, efficient, and flexible built environment.

3.5.2 Potential operationalization of the proposed framework

It is possible to discuss a proposed conceptual framework for design for adaptability concerning its ability to bridge the gaps in extracting and transmitting data between enablers of DfAd and customer needs. Architects, engineers, contractors, and customers should be able to exchange information and communicate systematically under the framework. The initial step to developing a framework would be to identify the different enablers of DfAd and their specific data requirements. Data on energy efficiency, thermal comfort, building systems, lighting, and structural components could be collected. By identifying the enablers and requirements, the framework can focus on developing a standardized method for extracting and transmitting data. Using digital visualization tools would allow customers to evaluate different design options and provide feedback. By establishing a systematic and standardized approach to data exchange and communication, the proposed conceptual framework aims to bridge the gap between enablers of DfAd and customer requirements. This way, the framework can ensure that customer requirements are incorporated into the building design process, making the buildings more adaptable and responsive as needs change. A suggested framework for adaptable building through modularity, DfMA, and digital fabrication: 1) Identify project requirements and design objectives, such as building performance, flexibility, modularity, and Sustainability. 2) Identify modular systems and components architects may use to create flexible and adaptable buildings. 3) Develop a modular building incorporating the identified modular systems and components.

Digital design tools, such as Building Information Modeling (BIM), can optimize the design of a building and ensure that it meets the project's requirements. 4) Consider the building's life cycle and adaptability: In BIM and computational design, future adaptations of a building can be simulated and visualized. 5) To produce high-quality modular components, utilize digital fabrication techniques, such as 3DP, CNC machining, and robotics. 6) Monitor and optimize the performance of the building using building technologies. 7) Design, construct, and operate following a circular economy approach. Utilize sustainable and recyclable materials, minimize waste and energy consumption, and design end-of-life reuse and recycling products. Also, the following figure illustrates the possible implementation of the framework in the design and fabrication process. It starts with pre-design by defining requirements for OSC design and fabrication and goes till the building's assembly and disassembly in on-site construction; quality control exists in each process (Figure 3.6).

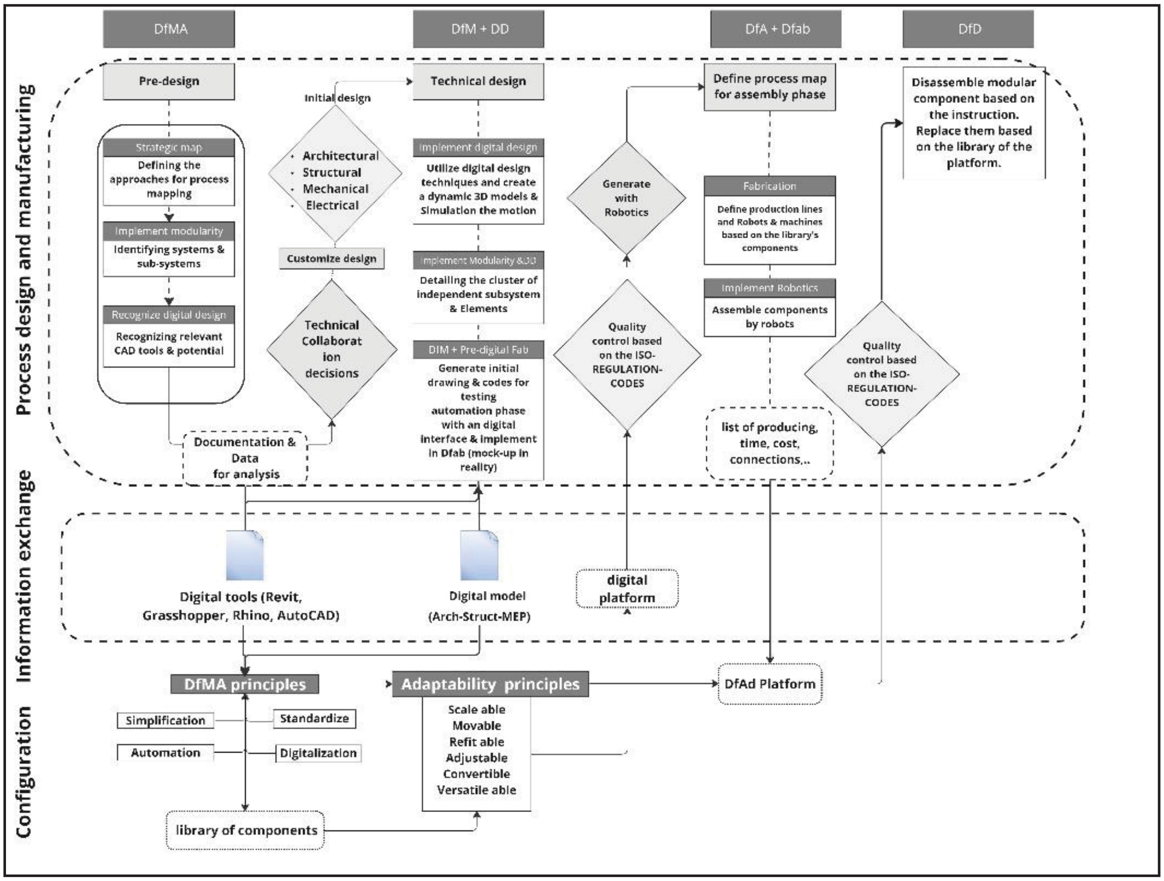

Figure 3.6 Possible operationalization of the proposed framework based on modularity and DfMA, DfMAd and DfD

In the future, research using this framework can assist in designing and building flexible and adaptable buildings. Implementing it in a BIM environment would allow for an integrated project management process involving all stakeholders, resulting in more efficient and adaptable buildings.

3.6 Conclusion

In conclusion, the proposed conceptual framework for design for adaptability has the potential to offer operational support to architecture, engineering, and construction with the aim of circularity. By integrating the principles of modularity, DfMA, digital design, and fabrication, the framework offers a systematic approach to designing adaptable building systems that are

flexible, sustainable, and cost-effective. Using digital tools and techniques enables rapid prototyping, iteration, and customization. In addition, the emphasis on collaboration and communication between stakeholders encourages a more holistic and integrated approach to building design and construction. This framework offers designers, engineers, fabricators, and other stakeholders a practical roadmap. It can enable a shift toward more efficient, sustainable, and innovative building practices. Architects, designers, contractors, and manufacturers should collaborate to establish industry-wide standards and the most effective procedures and improve all stakeholders' access to technology and resources. Designers can explore various design options and quickly iterate through different scenarios with digital design tools. These include parametric modelling and generative design. By enabling real-time analysis and simulation, digital design can help identify and mitigate potential architectural problems, such as construction errors. However, further research and testing are necessary to validate and refine the framework's implementation in real-world contexts. While modular and DfMA approaches and digital design and fabrication technologies offer significant benefits for adaptable building design, there are still some challenges to reaching their full potential fully.
Acknowledgement: The authors are grateful to the Natural Sciences and Engineering Research Council of Canada for the financial support (Grant RGPIN-2020-05641).

The Bibliography section is presented at the very end of the thesis.

3.7 Synthesis of findings to inform the proposed framework

The field of education is constantly evolving and changing in today's fast-paced world. Education institutions must adapt to changing pedagogical approaches, technological advancements, and the changing needs of students and educators. As part of this case study, the conception, design, and implementation of an innovative and adaptable educational building that is a model for flexible and responsive learning environments are explored. A suitable educational building should take into account the following factors:

- Design and Digital Fabrication Elements: there are four main factors that essential in designing the interior spaces, exterior elements and façade (Figure 3.7).

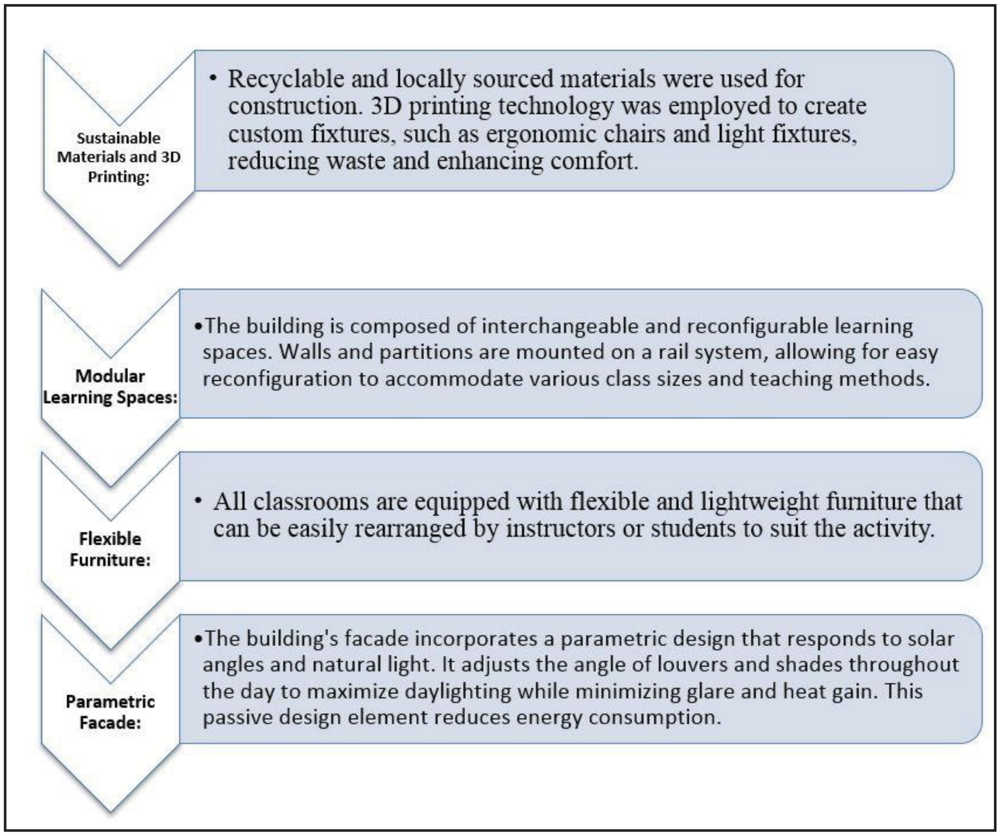

Figure 3.7 Findings of adaptable Interior and exterior spaces and elements

Adaptability in function: there are two main approaches in designing the interior educational spaces that can increase the level of adaptability (Figure 3.8).

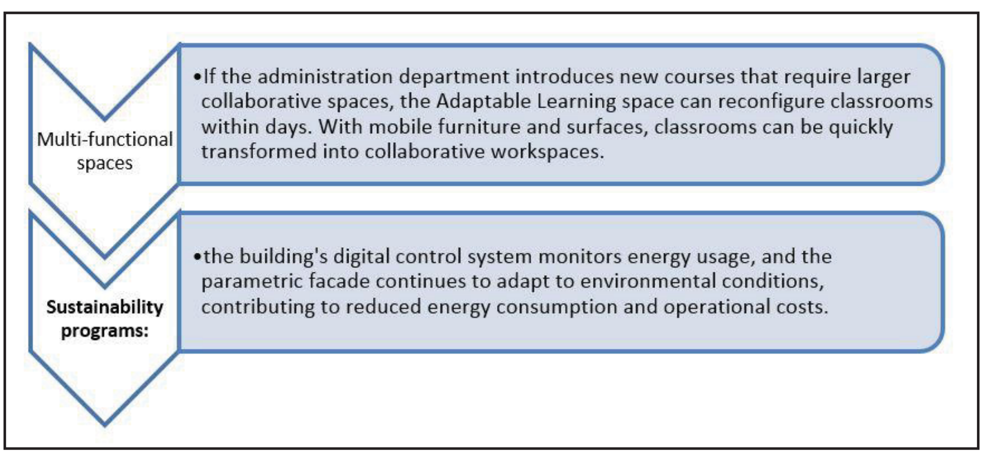

Figure 3.8 Factors of adaptability in functions

Results and Impact of adaptability include (Scaradozzi et al., 2021)/ (Bradbeer et al., 2017)/ (Malinin, 2017)/ (Dovey & Fisher, 2014):

- Enhanced Learning Experience: The Adaptable Learning Hub has significantly improved the learning experience for students and educators, enabling a more interactive, flexible, and responsive environment.
- Community Engagement: The building has become a hub for community engagement, hosting many events that benefit the institution and the surrounding neighbourhood.
- Sustainability: The adaptive design and sustainable features have reduced energy consumption, lowering the building's environmental footprint and operational costs.
- Future-Proofed: GAT can continue to evolve and adapt its educational offerings without the need for major construction projects, saving time and resources.

"The Adaptable Learning Hub" showcases the potential of digital fabrication, parametric design, and flexible architecture in creating educational buildings that can seamlessly adapt to changing pedagogical needs, foster sustainability, and engage the community. It serves as a model for educational institutions looking to future-proof their infrastructure.

3.7.1 Artifacts - Digital design and fabrication process of adaptable interior and exterior elements

It is possible to reconfigure spaces quickly and efficiently using these elements, resulting in a dynamic and effective learning environment. Digital design, digital fabrication, and modularity are crucial in achieving adaptability. As a result, they allow precise customization, flexibility, and sustainable solutions in the design of adaptable interior and exterior elements by emphasizing modularity and spaces to meet changing requirements while maximizing resource efficiency. Digital design, digital fabrication, and modularity are crucial in shaping adaptable elements within educational buildings. It discusses real-world case studies, challenges, lessons learned, and future directions in this multifaceted field, emphasizing the importance of adaptable and modular solutions.

3.7.1.1 Principles of adaptive digital design

Digital design, in the context of adaptable elements, adheres to several fundamental principles:

1. Adaptability and Modularity: Digital design allows for the creating of modular components and systems to meet changing requirements. This adaptability is akin to the principles found in kinematics, where movements and arrangements are mathematically understood and applied to design adaptable mechanisms within the building (Moloney, 2011).
2. Parametric Modeling: Parametric design principles establish relationships and dependencies between design elements, much like fractals in nature exhibit self-similarity across scales. Parametric models can generate particular patterns and structures that repeat and scale in a fractal manner, ensuring modification at various levels of detail (Mariano & Pereira, 2020).
3. Customization: Digital design permits customization at a different level. Origami-inspired designs can be employed to develop adaptable surfaces and structures. As an example, the box-unit, composed of light-gauge steel-framed edges including walls, floors, ceiling, and service cabinets, allowed for various user-defined configurations. This adaptability contributed to lower construction costs and increased production capacity. The modular design enabled the units to be easily juxtaposed or stacked, with simplified stitching through structural edge members, illustrating the potential for factory-produced adaptable housing (Bellemare et al., 2017).

3.7.1.2 Role of BIM in parametric design

- Building Information Modeling: BIM, coupled with kinematic principles, allows for the simulation and visualization of complex movements and transformations within adaptable spaces. It enables architects and designers to model how elements such as walls, partitions, and furniture can dynamically shift to meet changing needs (Lu & Korman, 2010)/ (Follini et al., 2020).

- Parametric Design: In fractal-inspired design, parametric modelling can generate flexible patterns that exhibit self-similarity at various scales. These patterns can be applied to interior and exterior elements, creating a visually harmonious and adaptable environment (Mariano & Pereira, 2020).

3.7.1.3 Integration of sustainability in digital design

- Sustainable Materials: Digital design, inspired by origami's efficient use of material, can optimize the selection and layout of sustainable materials. Minimizing waste and maximizing resource efficiency aligns with sustainability goals (Guo, 2022)/ (Megahed, 2017).
- Daylighting and Natural Ventilation: Kinematic principles can be applied to design adaptable sunshade systems that respond to the sun's position throughout the day, optimizing daylighting while minimizing heat gain. Natural ventilation strategies can also benefit from adaptable designs that respond to wind direction and outdoor conditions (Moloney, 2011).
- Energy-Efficient Systems: Digital simulations can assess the energy performance of adaptable spaces inspired by fractal principles. The iterative and self-similar nature of fractals can inform the design of energy-efficient HVAC systems that adapt to various room configurations, optimizing comfort and energy use (Thill, 2020).

In summary, digital design principles for adaptable elements can draw inspiration from kinematics, fractals, and origami to create flexible, customizable, efficient, and sustainable spaces. These interdisciplinary approaches offer innovative solutions for educational buildings that seamlessly adapt to evolving pedagogical needs while minimizing environmental impact.

3.7.1.4 Adaptable interior elements

1. Movable walls
   - These walls have a digital control system with the factor of repositioning (Cleveland et al., 2023).

- Movable walls facilitate the creation of various room configurations, from traditional classrooms to open collaborative spaces (Grannäs & Stavem, 2021).
- They adapt to different teaching methods, enabling quick transitions between lectures, group discussions, and project-based learning (Cleveland et al., 2023).

2. Modular furniture
   - Modular furniture pieces, digitally designed and fabricated, are versatile and customizable (Temel & Kahraman, 2018).
   - Furniture modules aid in creating flexible seating arrangements that accommodate large lectures and small group activities (Temel & Kahraman, 2018).
   - Students and instructors can configure furniture to suit their preferences and teaching styles, promoting a dynamic learning environment (Scaradozzi et al., 2021).
3. Interactive displays
   - Digital interactive displays are integrated into adaptable interior elements, providing dynamic function (Achten, 2019).
   - Instructors can adapt content delivery in real-time, catering to diverse learning preferences and engaging students more effectively (Scaradozzi et al., 2021).

3.7.1.5 Advantages for accommodating needs

1. Enhanced flexibility
   - Adaptable interior elements offer the flexibility needed to have transition between different teaching and learning modes (Schulze & Pinkow, 2020).
   - Instructors can easily modify the classroom layout to align with their instructional objectives, accommodating lectures, group work, or hands-on activities (Scaradozzi et al., 2021).
2. Optimized space utilization
   - Movable walls and modular furniture maximize space utilization by efficiently using square footage (Duthilleul, 2018).

- This optimization ensures that the learning environment is scalable and can adapt to changing enrollment sizes and curricular demands (Cleveland et al., 2023).

3. Customized learning experiences
4. Promotion of collaboration
    - Adaptable elements foster collaborative learning by creating open, inviting spaces (Malinin, 2017).
    - They encourage student interaction and teamwork, enabling group projects, peer teaching, and thinking sessions (Baars et al., 2023).
5. Increased engagement
    - Interactive displays capture students' attention and boost engagement through interactive content and presentations (Pereira et al., 2018).
    - The dynamic nature of these elements helps maintain student interest throughout lessons (Malinin, 2017).
6. Future-proof and future need
    - Adaptable interior elements are designed with the future in mind, ensuring that educational spaces remain relevant as teaching methods evolve (Emilia Plotka et al., 2016).
    - They support innovative pedagogical approaches and emerging technologies, making the learning environment future-proof (Pereira et al., 2018).

Incorporating digitally designed and fabricated adaptable interior elements into educational spaces enhances the physical environment and fosters a more inclusive, engaging, and responsive educational experience. These elements empower educators to cater to diverse teaching and learning needs, promoting effective and adaptable education.

3.7.1.6 Adaptable exterior elements

1. Dynamic facades
    - Dynamic facades include the ability to adjust their appearance, shading, or ventilation properties based on environmental conditions or user preferences.

   - These facades can adapt to control natural light, optimize thermal comfort, and respond to changing weather conditions, creating a more comfortable and energy-efficient outdoor environment.

2. **2.** Flexible outdoor spaces
   - Outdoor spaces are designed with flexibility, allowing them to serve various purposes and adapt to different activities (Scaradozzi et al., 2021).

Within the area of adaptable building design, this section examines the significant contributions made by digital design and fabrication. It is possible for architects and designers to create customizable and adaptable building solutions by leveraging digital tools and fabrication techniques. By highlighting the transformative effects of digital design and fabrication, this section aims to highlight how buildings are able to dynamically respond to changing environmental conditions and demands.

1. Parametric Modeling: Digital design, utilizing parametric modelling, allows architects to create dynamic facade designs that respond to changing variables like sunlight angles, wind direction, and temperature. These models inform the fabrication of adaptable facade components (D. A. Elmokadem et al., 2016).
2. Precision Fabrication: Digital fabrication technologies, such as 3D printing and CNC machining, ensure precision and accuracy in creating the components needed for dynamic facades and flexible elements. This precision is crucial for seamless adaptation (Eversmann & Studio, 2017).
3. Simulation and Testing**:** Digital simulations and testing tools enable architects to predict the exterior elements' performance in different scenarios to refine designs for optimal adaptability and functionality (Vazquez & Jabi, 2015).

Role of Environmental Sustainability:

1. Energy Efficiency: Adaptable exterior elements aid in optimizing energy use. Dynamic elements, for instance, can reduce heating and cooling demands by controlling solar heat gain and natural ventilation. This sustainable approach lowers energy consumption and operational costs (Kolarevic, 2003).

2. Natural Resource Conservation: Sustainable materials and construction techniques are employed to minimize resource consumption during the fabrication of exterior elements. Digital design ensures efficient material usage and minimal waste generation (Holstov et al., 2017).
3. User Comfort: Adaptable exterior elements play a vital role in creating comfortable outdoor environments. By controlling factors like shading and thermal comfort, they encourage outdoor use year-round, reducing the need for energy-intensive indoor spaces (Andia & Spiegelhalter, 2015).
4. Long-Term Sustainability: The adaptability of exterior elements extends to their long-term sustainability. Designs account for maintenance needs, and digital monitoring systems can assess the performance of sustainability features over time, ensuring continued environmental benefits (Holstov et al., 2017).

In summary, adaptable exterior elements in educational buildings, including dynamic facades and flexible outdoor spaces, are shaped by digital design and fabrication techniques. These elements optimize energy efficiency, conserve natural resources, and prioritize user comfort while contributing to the sustainability and environmental responsibility of the educational facility. They enhance the overall learning experience by providing adaptable, eco-friendly outdoor environments.

Challenges Encountered:

1. Complexity of Digital Models: Designing adaptable elements with digital tools involves complex parametric models. Managing the details of these models, especially in large-scale projects, can be challenging and resource-intensive (Aguiar et al., 2017). The goal is to develop a tool in Rhinoceros with Grasshopper to input various parameters and output a building ready for CNC cutting, linking CAM and CNC technologies with parametric design software for economical, individualized components (Kaiser et al., 2019).
2. Material Selection: Choosing suitable materials for digital fabrication can be tricky. Ensuring that materials are adaptable and durable while aligning with requires careful

consideration (Slepicka et al., 2021). Digital manufacturing allows standard materials to create non-standard architecture through file-to-factory strategies, integrating CNC milling (Kaiser et al., 2019).

3. Interdisciplinary Collaboration: Effective collaboration among architects, engineers, fabricators, and contractors is essential. Bridging communication gaps and ensuring that everyone understands the digital design's intent can be challenging (Lu & Korman, 2010). Modular construction involves offsite fabrication of structural units, completed with essential installations. It offers benefits like reduced workforce needs, lower greenhouse gas emissions, and improved schedules and quality. However, extensive planning and interdisciplinary coordination have hindered its adoption. Building Information Modeling (BIM) can address these challenges and its ability to streamline interdisciplinary efforts (Lu & Korman, 2010).
4. Cost Management: Digital design and fabrication can be cost-intensive, particularly in the initial stages. Balancing innovation with budget constraints is a constant challenge (García de Soto et al., 2018). For example, a study assessing digital fabrication (dfab) for constructing a robotically-fabricated complex concrete wall found higher productivity and economic benefits compared to conventional methods (García de Soto et al., 2018).
5. Technological Limitations: Keeping up with the latest digital design, fabrication technologies, and software updates can be demanding. For instance, the production system faced significant challenges due to material waste from plywood and sawdust, which were difficult to recycle. CNC wood milling contributed to this waste. Additionally, the shelter was overengineered with overly close stud spacing and excessive attachments. A thinner material with fewer connections could have sufficed. Converting design models to interlocking components was also time-consuming, taking approximately four working days (Sass, 2007).

Ensuring compatibility and optimizing workflows can be a persistent challenge. The strategies include the following points as:

A. Early Prototyping: Prototyping adaptable elements in more minor scales before full-scale fabrication allows for testing and refining of designs. This approach helps identify issues and reduce errors (Dunn, 2012a).
B. Sustainability and Material selection: Using and testing sustainable materials pays off in the long run. Collaboration with material experts can aid in making informed choices (Iwamoto, 2009). For instance, Helios House is designed as a green gas station to promote environmental stewardship through education and dialogue. It maximizes sustainability and energy efficiency in its water, heat, energy, lighting, and material systems. The canopy design is its most iconic feature. Using 3,500 recycled cardboard molecules in only two shapes, the Digital Origami concept reinterprets traditional space (Iwamoto, 2009).
C. Cost-Benefit Analysis: Conducting thorough cost-benefit analyses helps make informed decisions about allocating digital design and fabrication resources (Gramazio & Kohler, 2014).
D. Technological Training: Continuous training and upskilling of team members in the latest digital design and fabrication tools are crucial. Regularly evaluating and adopting new technologies can improve efficiency (Dunn, 2012b).

Informed Future Design Decisions:

1. Streamlined Workflows: The challenges encountered during the digital design and fabrication phases have prompted the development of streamlined workflows. Lessons learned in managing complexity have led to more efficient processes (Gramazio & Kohler, 2014).
2. Technological Integration: A commitment to staying at the forefront of technology informs future design decisions. Projects are designed with compatibility and scalability, ensuring they remain adaptable to evolving digital tools (Gramazio & Kohler, 2014).

In conclusion, challenges encountered during the digital design and fabrication phases have resulted in valuable lessons and strategies for improving the process. These experiences have informed future design decisions, leading to more efficient workflows, sustainable material choices, enhanced collaboration, informed budget allocation, and a commitment to staying technologically current. These adaptations successfully create adaptable interior and exterior elements in educational buildings. The key Takeaways includes the following points:

- Digital Design and Fabrication: Digital design and fabrication are pivotal in creating adaptable interior and exterior elements within educational buildings. These processes enable precise customization, flexibility, and sustainability in design and construction.
- Modularity and Parametric Design: Modularity and parametric design are fundamental to adaptability, allowing flexible configurations and dynamic adjustments to meet changing teaching and learning needs.
- Sustainable Integration: Sustainability is essential in shaping adaptable elements. Sustainable materials, energy-efficient systems, and environmental considerations integrate into the design and fabrication process.
- Interdisciplinary Collaboration: Effective collaboration among architects, engineers, fabricators, and stakeholders is crucial. Clear communication and shared understanding are essential to successful outcomes.

Integrating adaptable interior and exterior elements profoundly impacts the overall educational experience within the building. These elements enhance flexibility, allowing educators to transition seamlessly between teaching methods. They optimize space utilization, ensuring that every square foot serves the educational mission efficiently. Moreover, they create comfortable, sustainable, and engaging environments that inspire learning and collaboration. Ultimately, adaptable elements contribute to creating dynamic educational spaces that evolve alongside the needs of students and educators, elevating the quality of education and fostering innovation within the institution.

3.8 Intro to design a mechanism

This section introduces the concept of designing a mechanism for adaptability within buildings through the integration of digital design, fabrication, and modularity. A key objective of this study is to examine how digital technologies can be used to produce flexible and responsive architectural solutions. Systems that can adapt to changing needs and environments are being developed using modular construction techniques and digital fabrication techniques. During this introductory phase, further exploration of adaptable building mechanisms will be conducted, focusing on harnessing the potential of digital tools and modular construction methods. The following scheme (Figure 3.9) indicates the general process of digital design techniques. This scheme has input, output, mechanism, evaluation & control, and simulation process to generate the final artifact.

- Specification of Inputs and outputs: Links & frame, Kinematic pairs, Connecting lines & points, Angles, Types of Connections
- Mechanisms: The function of mechanism, Degrees of freedom (DOF), Transformation of forces, Motion
- Evaluation & Control: Analysis of mechanisms, graphical, analytical, and numerical data
- Simulation: The Mechanism

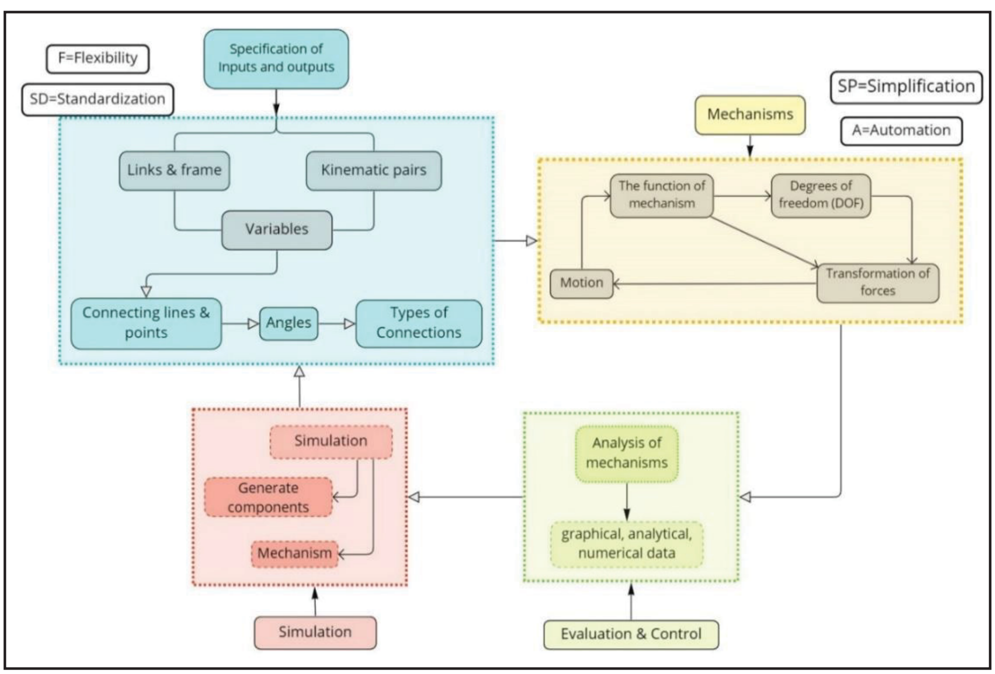

Figure 3.9 Main parts of a kinematic technique used in this project

3.8.1 Dynamic vertical and horizontal surfaces based on defining mechanism

Based on this diagram (Figure 3.10), two methods involve two directions: the V-hydraulic jack and the H-hydraulic jack. The V-hydraulic jack is an inclined beam with a hydraulic cylinder attached, while the H-hydraulic jack is vertical beam with a hydraulic cylinder attached. Both are used to lift heavy objects but have different lifting capacities. The V jacks are derived from slab concrete shoring systems, while the H jacks have pull-up bar systems. Jacks help lift heavy objects. In addition, jacks are available in various sizes and can lift a range of weights depending on their size. Jacks function primarily by applying force. The force includes the pressure of the hydraulic fluid, which pushes against the pistons inside the jack. The piston moves up and down, applying pressure for movements. The force of the hydraulic fluid is strong enough to lift heavy objects.

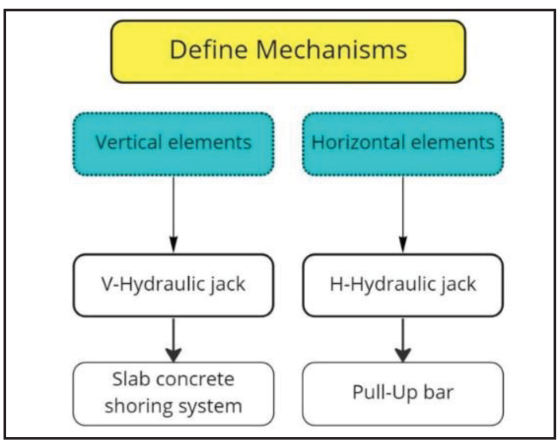

Figure 3.10 Two systems of defining an adaptable mechanism

Grasshopper aids in generating algorithmic models to design shapes according to specific parameters. The parameters are the length and width of the wall. Also, the details of connections are parts of the design process. According to Figure 3.11, the vertical elements have movements with V-Hydraulic jack. The holes between surfaces include extra layers, such as gypsum. This model is an example of a primary concept showing the function of kinematic surfaces.

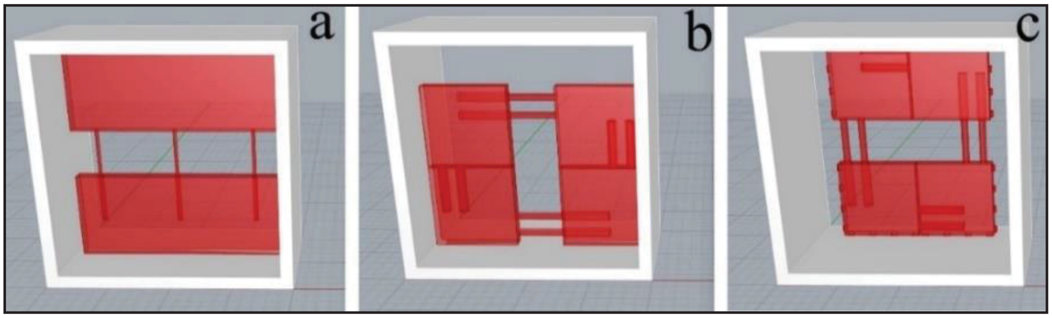

Figure 3.11 Dynamic vertical surfaces

Figure 3.12, shows how the horizontal elements have movements with hydraulic jacks. The holes between surfaces involve different layers of metal or wood.

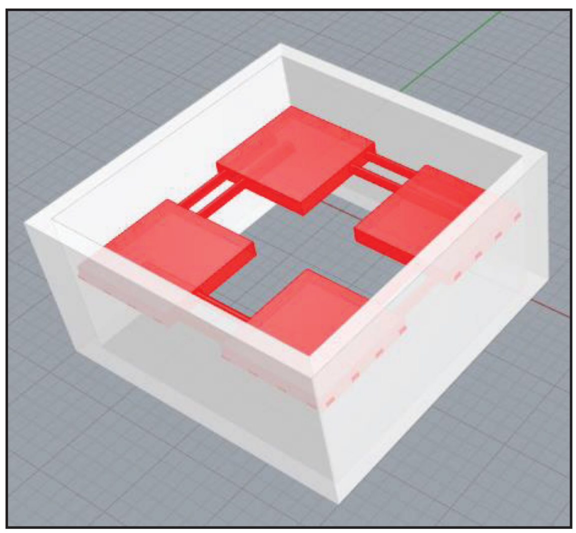

Figure 3.12 Dynamic horizontal surfaces

All of these concepts are in the early stages of development, helping to enhance flexibility and adaptability. Furthermore, these concepts can transform monofunctional spaces into multifunctional ones. Flooring elevations also can be changed. Depending on the shearing layers, a space plan with services such as mechanical and electrical pipes and equipment is selected. The permanent elements are designed based on the space plan. In designing for adaptability, they can be used to explain geometric principles and the advantages of using mechanisms. Grasshopper's components and plugins aid to develop adaptive design models that consider defining mechanisms. This project's permanent elements are vertical and horizontal surfaces (walls, floors, columns, beams), (Figure 3.13, 3.14).

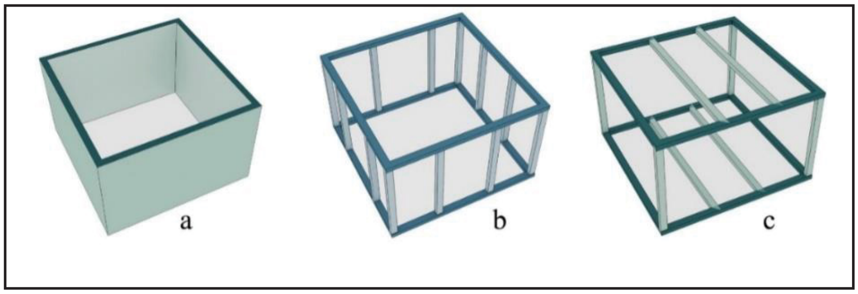

Figure 3.13 Permanent elements: a) walls, b) columns, c) beams

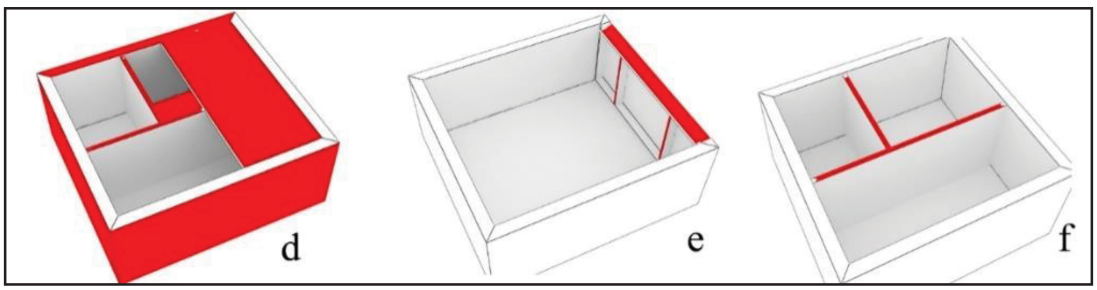

Figure 3.14 Space plan: d) walls, ceilings, floors,
e) prefabricated wall panels, c) rooms

It is increasingly important in modern architecture to focus on adaptability so that the structure can meet future demands. The Grasshopper tools enable architects to visualize and simulate these concepts, making it easier for them to communicate their innovative ideas and ensure that they are feasible. A kinematic design that integrates with a building management system allows automated adjustments based on predetermined conditions or sensors. Using sensors, walls or floors can be rearranged automatically in response to occupancy patterns or environmental conditions. The use of floors and walls that can be adjusted kinematically to accommodate people with disabilities can improve accessibility. To ensure safety and reliability, kinematic movements must be incorporated into the design of walls, floors, and ceilings.

CHAPTER 4

DEVELOPING ADAPTIVE EDUCATIONAL SPACES THROUGH A THEOROTICAL FRAMEWORK BASED ON MODULARITY AND DIGITAL DESIGN

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Abstract

As education undergoes significant transformations, conventional building designs have limitations accommodating evolving needs. Encountering retrofitting complexities, resistance to change, inflexible structures, resource constraints, and underutilized spaces can impede the implementation of essential changes in educational infrastructure, potentially resulting in obsolescence. Also, Addressing the limitations of conventional building designs in the face of evolving education involves prioritizing adaptable design principles, leveraging digital technology, fostering community integration, emphasizing sustainability, and encouraging ongoing innovation. This study proposes a theoretical framework to create adaptable educational facades and spaces. Adaptable infrastructures are designed using the Design Science Research (DSR) methodology. The methodology of this paper consists of the following steps: developing theoretical framework involves identifying relevant theories and concepts and then illustrating relationships with a conceptual model.

After that, an operationalized framework design transforms a theoretical framework into simulation artifact. The research illustrates how designers can create dynamic learning environments using kinematics and parametric design. It provides significant visions into the mechanisms that facilitate this integration, including modularity, flexible junctions, and the crucial role of digital design in enhancing adaptability and controlling transparency. In achieving these objectives, the research aims to provide a comprehensive framework for advanced adaptable wall screens. The Adaptable Learning Center improves dynamic learning

environments with modularity and digital methodologies. In addition to education, it facilitates diverse local activities. The flexible design of this product emphasizes sustainability and operational efficiency through digital enhancements and modular features. The research presents a framework emphasizing modularity, digital design, and adaptability in shaping future educational architecture through nature-inspired mechanisms.

Keywords: kinematics, adaptability in educational buildings, mechanism, parametric design.

4.1 Introduction

There is rapid change in educational requirements, and traditional building design have difficulty adapting. The ongoing growth of the population and increasing urbanization, coupled with the need to accommodate different programs, activities, and services, have heightened the need for flexible architectural design in educational space infrastructure (Kendall & Teicher, 2000). Assuring accessibility to facilities and services for a broad range of users requires adaptable spaces and meeting educational requirements (Cleveland et al., 2023). Education infrastructure can be hindered by retrofitting complexity, resistance to change, and inflexibility in these design. Physical spaces play an essential role in supporting teachers and educational systems in meeting the needs of students as they develop.

As the Ministry of Education's 2011 discussion cited in Bradbeer, 2017, "Flexible learning spaces" represent a significant shift in educational discourse, emphasizing new approaches to teaching and learning (Bradbeer et al., 2017). Y. Duthilleul, 2018, discusses the need for educational spaces to be reconfigured to meet various needs, including the ability to move walls as needed (Duthilleul, 2018). Additionally, he emphasizes the importance of having spaces that can be changed to fill the needs of various groups throughout the school year and day. Multipurpose spaces that promote social interaction are included in these spaces. Modern educational space design, known as ILE (Innovative Learning Environment), prioritizes flexible spaces for diverse teaching methods and individualized learning [5]. Transitioning to

ILEs involves architectural changes and a shift in teaching methods to fully utilize these spaces, offering versatile classrooms, breakout areas, and shared spaces for various activities, supporting personalized and collaborative learning. It is possible to view ILEs as a methodological strategy for driving change in educational practice (Grannäs & Stavem, 2021). Also, flexible structures with modular designs can be adapted to long-term changes, while flexible elements such as operable walls and furniture can accommodate diverse learning activities and group sizes [6]. Modularity allows customization. Design regulations can be adjusted to maximize resource efficiency by incorporating natural (Emilia Plotka et al., 2016). Furthermore, factors such as thermal comfort, air quality, lighting, and, most importantly, acoustics can improve students' academic success by improving their comfort level. For contemporary learning environments to be successful, stakeholders must address critical issues related to education, collaboration, and design (Woodman & BEN CLEVELAND, 2011). Historically, the educational infrastructure has been resistant to change. This resistance makes updating and improving the physical learning environment challenging. Innovative teaching and learning practices may be hindered by it.

In addition, Askar 2021 stated that adaptable and flexible construction has consistently dealt with the problems of building "obsolescence" and "redundancy." Furthermore, the following connection can be made: 1) Innovative architectural practices include modularity and digital design in educational spaces. Combining architectural concepts and technology can create a dynamic and adaptable learning environment. 2) The term "Adaptive Educational Spaces" implies that the architectural design responds to changing educational needs. Architecture have a substantial role in supporting the evolution of pedagogical approaches and teaching methods. 3) A mention of "digital design" emphasizes integrating technology into the architectural process. Digital tools and techniques are utilized to enhance the adaptability and functionality of educational facilities. According to K. Patelia et al. 2013, by applying the modular system to a building's design, the dimensions and scales of elements and assemblies, installation, details, and service systems can be identified by the designer, engineers, manufacturer, etc. They stated that the modular design could provide coherent coordination between dimension, scale, and position of different elements and spans in the structure of the building [8]. Also, modularity aids in enhancing quality, reducing cost, making more creative alternative designs, collaborating between designers, contractors, manufacturers, clients, and users, etc. (Ro et al., 2007). Digital technology is rapidly advancing and is being applied to the construction process by architects and engineers. For instance, computer-aided design (CAD) enabled designers to convert drawings into a digital format (Smorzhenkov & Ignatova, 2021). In architecture, the computer is used as a digital drawing board, allowing the user to modify, reproduce, and enhance the accuracy of the drawing (Bazalo & Moleta, 2015). This paper indicates significant link between architecture, adaptability, technology, and pedagogy, emphasizing the holistic nature of modern educational design. An integrated design approach underscores the importance of a comprehensive and theoretical framework for designing educational spaces. Architects are concerned with the physical structure and how architects can design spaces to meet students' and teachers' educational needs.

Traditional building design are not flexible enough to adapt to the evolving needs of modern education, leading to the issue of obsolescence in the existing educational infrastructure. Conventional teaching methods, pedagogical approaches, and technological advancements cannot easily be incorporated into these design. This study explores the design and adaptability of educational spaces comprehensively. A functional framework based on modularity and digital design potential, like the kinematics concept, is being developed to achieve the objective. A further objective of the project is to simulate an artifact within an interior educational environment to control transparency and privacy. Research in this area aims to provide valuable insights into the advancement of adaptable learning environments, thus enhancing the future of educational architecture design. The Objectives and hypothesis of this paper are followed as:

Objective: Create a framework of modularity and digital design as enablers for designing adaptable educational buildings. An evaluation of the framework will be pursued through a partial implementation using designed artifact.

Hypothesis 1: By integrating modularity principles and digital design techniques, interior elements such as walls can be transformed into adaptable components that effectively respond to evolving functional needs and aesthetic preferences while upholding structural stability.
Hypothesis 2: A high degree of configurability will be achieved using the proposed framework, allowing for timely adjustments to changing user needs, advancing technology, and changing building lifecycles, ultimately resulting in more sustainable and adaptable built environments.

4.2 Literature review

This research begins with a literature review to provide an overview of the current research in the field. Additionally, the section discusses different alterations that can occur to the architectural configuration and intended purpose of a building over time, including adaptability and flexibility, key terms related to the study.

4.2.1 Terminology of adaptability

Terminology related to adaptability in various contexts can include Flexibility, Adaptability, and congestion. According to Y. Duthilleul, 2018, regarding the adaptable educational building, flexibility and adaptability span three-time horizons [4], figure (4.1, a): long-term, medium-term, and short-term. There are three criteria by which a building can adapt to the changes:

- Adaptability: The ability to make substantial changes to the building over the long term, such as expanding it to accommodate more students.
- Adjustability: The capability to reconfigure parts of the building in the short to medium term to create different spatial arrangements.
- Agility: The ability to quickly adapt settings, furniture, and IT equipment to changing needs.

Also, Figure (4.1, b) shows the difference between adaptability and flexibility (Kamara et al., 2020). J. M. Kamara et al. 2020, expressed that flexibility refers to rapid, short-term, and frequent changes. However, adaptability refers to low-frequency alterations over a long time. Long-lasting changes could happen in the structural part of the building. Another term for it is congestion, which refers to very short-term changes such as unexpected increases in demand for space.

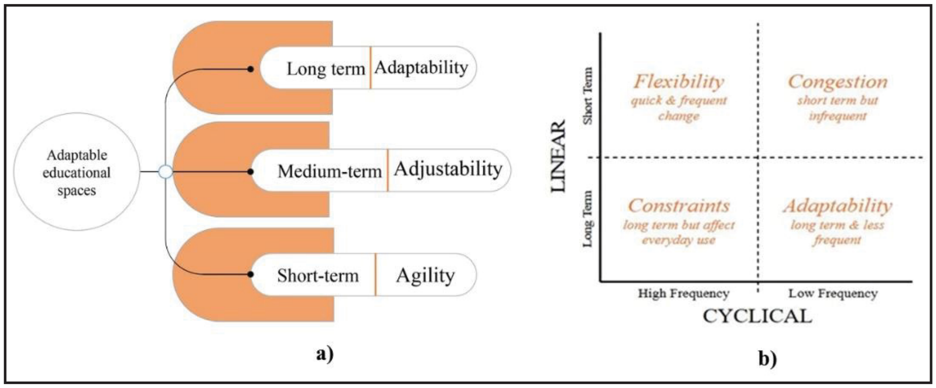

Figure 4.1 a) Level of Adaptability in educational spaces,
b) differentiation between adaptability and flexibility
Taken from J. M. Kamara (2020, p.3)

According to Cristiana Cellucci, 2015, flexibility aids in making a versatile and internal conversion in the building through the adaptability of the spatial layout and interior spaces. There are four major approaches to having flexibility in the structure as follows [13]: "Spatial flexibility in a fixed surface area," "Evolutionary spatial flexibility," "Technological flexibility related to construction techniques," "Technological flexibility related to the easy maintenance of the installations and building sub-systems." According to the American Heritage 2011, adaption is "to make suitable to or fit for a specific use or situation. Various adaptation strategies are defined by other authors as follows:

- Flexibility refers to having the potential to adapt to the changes due to the user's needs. In this term, components can be modified by the user's control, such as machine-driven and automatic techniques (Schneider & Till, 2005)/ (Kronenburg, 2005)/ [12].
- Active: In this term, the components can adapt to external changes like environmental changes by the user's intervention. The electrical techniques are essential in this case (Villegas et al., 2020).

- Dynamic: In this term, one system could be defined with one input to answer different changes. Computer-aided is required in this part (Scuderi, 2019)/ (Kendall & Teicher, 2000)
- Interactive refers to integration between the user's needs and the potential of the system to answer the changes. In this term, digital sensors and programming are essential (Holstov et al., 2017)/ (Achten, 2019)
- Intelligent: In this term, components can be modified and adapted to the changes by a system control. Intelligent system is conducted by computer program (Ralegaonkar & Gupta, 2010)
- Smart: In this term, components of the building can be modified by itself control. The system has a "self-initiative" feature. It can comprehend the changes and plan a scenario to adapt to the changes (Kolarevic, 2003).

4.2.2 Digital design application and kinematic movement in adaptability

Adaptable educational spaces utilizing digital design and kinematic movement represent a dynamic shift in architectural thinking and educational infrastructure. The innovative approach relies on technology and engineering principles to create learning environments seamlessly adapted to evolving pedagogical requirements. An overview of these concepts is provided below:

- Customization and Flexibility: Architects and educators can customize educational spaces with digital design technologies. The customization extends beyond fixed layouts and allows for various configurations that can be adapted to various requirements of educational spaces. Experimenting with different layouts and arrangements before the physical construction begins using virtual design tools is possible. Operational efficiency, user-friendly interfaces, graphical representations of processes, adaptability to changing requirements, and significant productivity gains are some advantages of virtual design tools (VDT) (Ma et al., 2021a)/ (Shang & Zhang, 2022)/ (Bakhshi et al., 2022).

- Visualization: Using digital design, stakeholders can visualize educational spaces in 3D models, clearly understanding the space utilization. This visualization process allows real-time adjustments to ensure that the final artifacts and designs align with educational objectives (Mukkavaara & Sandberg, 2020)/ (Elma Durmisevic2, 2017).
- Dynamic Learning Environments: In kinematic movement, movable architectural elements, such as partitions, walls, or furniture, create dynamic learning environments. By adjusting these elements, different teaching methods and student activities can be accommodated quickly (Filipa Peres Frangolho Crespo Osório, 2019)/ (Tsiamis et al., 2018)/ (Cleveland et al., 2023).
- Optimized space utilization: Using kinematic movement ensures that educational spaces are designed to accommodate various activities and functions. Using a single room, one can transform it from a traditional lecture hall into a collaborative workshop, maximizing the use of space (Cleveland et al., 2023)/ (Seyrek et al., 2021)/.
- Accessibility support (Askar et al. - 2021 - Adaptability of Buildings A Critical Review on Th.Pdf, n.d.): Adaptable spaces with kinematic movement can be configured to accommodate students with diverse needs, ensuring that the learning environment is accessible to all.

Digital design and kinematic movement in adaptable educational spaces represent a progressive approach that aligns with the evolving nature of education. Through these concepts, educators are empowered to design flexible, technology-enhanced, and inclusive learning environments that respond to contemporary pedagogy's changing demands.

4.2.3 Role of modularity in digital design for adaptability

To achieve adaptable educational environments, modularity plays a vital role in digital design:

- Customization and Standardization (Bridi et al., 2019): With modularity, it is possible to create standardized building blocks or components that can be easily assembled and reconfigured. These components can be precisely tailored using digital design to meet facilities' specific needs.

- Rapid Prototyping and Iteration (Xu, 2009): Rapid prototyping of modular elements is enabled by digital design and modelling. By experimenting in a virtual environment, architects and designers can quickly evaluate different arrangements, sizes, and configurations. Through this iterative process, modular design is refined, ensuring that they are adaptable and functionally efficient.
- Scalability (Askar et al., 2021): The modular design principle is scalable. A digital design allows architects to easily extend or replicate modular components to accommodate or change needs. Whether adding additional rooms or expanding common areas, modularity can be used to scale spaces cost-effectively and efficiently.
- Sustainability (Bridi et al., 2019): Sustainability goals are aligned with modularity. Educational institutions can minimize waste and reduce environmental impact by reusing and reconfiguring modular components. Using digital design, architects can optimize the use of materials and resources when creating modular elements, contributing to sustainable building practices.

As a result of modularity in digital design, architects, educators, and educational institutions can design adaptable spaces tailored to the specific needs of today's students. Also, it provides a foundation for designing adaptable educational environments that are customizable, scalable and sustainable.

4.3 Methodology

Using a DSR methodology, the first step is identifying adaptable design criteria and educational requirements. A theoretical framework for developing adaptable mechanisms in educational spaces will be proposed. To enhance adaptability, a mechanism regarding the framework will be defined. This mechanism is based on modular design and digital design principles. Create detailed 3D models and simulations of the proposed mechanisms using digital design tools and software. Through this step, the function of the mechanisms that can control transparency will be explored in a virtual environment within the layers of the building. Iterate on the design is necessary to refine the mechanisms.

4.4 Conceptual framework for digital design for adaptability

In design for adaptability of educational spaces, it is imperative to consider various aspects that address evolving educational requirements. Indoor-outdoor transitions facilitate seamless movement between different areas within a building. The need for adaptability is aligned with the need for educational spaces that can be used in various ways. Transparency is increasingly important in educational space design as educational requirements evolve. Transparency fosters a connected and visible learning environment through open spaces and glazing. Educators and students can interact and collaborate. Privacy concerns should also be addressed in transparent spaces, balancing transparency and the need for privacy.

- Indoor and outdoor transitions: According to B. Cleveland et al. 2023, indoor and outdoor transitions should be designed with particular attention to elements that facilitate movement between indoor and outdoor spaces. The building's interior and exterior are connected by entrances, windows, courtyards, and other architectural elements (Cleveland et al., 2023).
- Transparency: educational space design increasingly integrates transparency through open spaces and glazing, aiming to create a connected, visible, and shared learning environment. It enhances connectedness by allowing visibility across spaces. Privacy concerns in transparent spaces can be addressed by using patterned glass finishes, balancing transparency with privacy (Duthilleul, 2018)/ (Kolarevic, 2003).

Depending on the building layers, a space plan with services such as mechanical and electrical pipes and equipment is selected. The permanent elements are designed based on the space plan. In designing for adaptability, they can be used to explain geometric principles and the advantages of using mechanisms (MARKS, 2016). Grasshopper's components and plugins are used to develop adaptive design models that consider defining mechanisms. Figure 4.2, illustrates indicators of adaptability within educational spaces, emphasizing the importance of flexibility, modularity, and digital integration. It also outlines the essential requirements for designing such adaptable environments, including flexible infrastructure, acoustic considerations, and adaptable lighting solutions. Additionally, this figure demonstrates the implementation of transparency through kinematic and digital design elements, featuring smart glass walls that offer visual connectivity and privacy control, enhanced by kinematic mechanisms for dynamic adjustments.

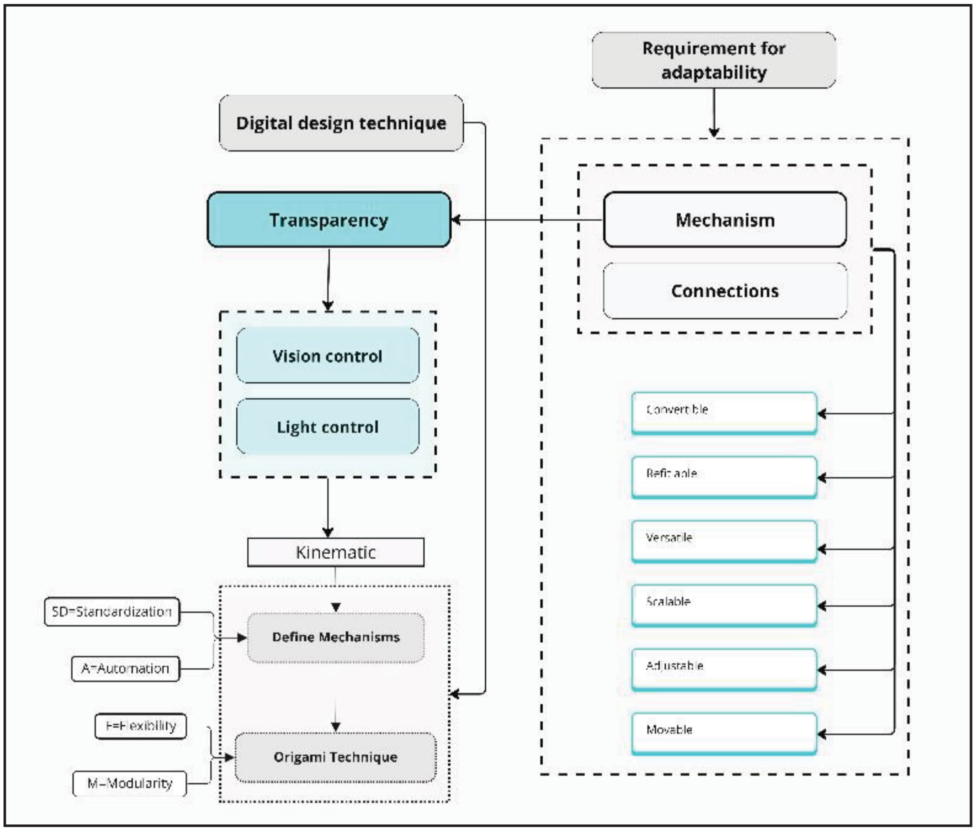

Figure 4.2 Indicators of Adaptability and Requirements

In the framework for developing adaptable mechanisms in educational spaces, three key steps are involved: design, manufacturing, and assembly. The mechanism is tailored during design to meet requirements and constraints, focusing on origami-inspired designs with iterative patterns. Motion and force analyses, aided by virtual simulations, help visualize functions and detect errors before manufacturing. Manufacturing involves crafting a precise physical prototype using robotics like Arduino, with any errors leading to architectural adjustments. The assembly process includes guidelines for seamless integration into educational settings. According to Figure 4.3, a mechanism can be addressed in three main steps: design, manufacturing and assembly.

- Design process: Based on functional requirements and constraining conditions, the mechanism can be defined. In this figure, a kinetic mechanism will be assessed. This mechanism can use retractable or unfolding patterns, origami, or 'Voronoi' patterns. In the analysis of a mechanism, the motion and forces should be recognized. These items aid in transferring and moving elements. The movement function should have a schematic illustration to customize the movement based on requirements. For this purpose, a parametric tool can be used. Finally, a virtual simulation aids in illustrating all functions, errors, conditions and results before manufacturing (Peters et al., 2013).
- Functional requirements refer to specific performance criteria and functionalities the components must meet to achieve their intended purpose. The kinetic construction elements meet these requirements to function effectively. These requirements can be: 1. Specify the required range of motion for the kinetic elements. 2. Timing and speed: Establish the timing and speed of the kinetic elements. 3. Specify the lifespan and resistance of the kinetic elements. 4. Describe the control systems and interfaces for the kinetic elements. Sensors, actuators, and automation technology are all included in this process. 5. Set energy efficiency goals for the kinetic elements, ensuring that they consume minimal amounts of energy or incorporate renewable energy sources. Ensure that the kinetic elements are user-friendly and meet the needs of the users (Youssef, 2017)/ (Barozzi et al., 2016a)/ (Sedky, 2021)/ (Phocas et al., 2012)/ (Elkhayat, 2014).
- Manufacturing process: In this step, a physical prototype will be generated by the use of a technical system such as Arduino. Also, the motions and movements will be indicated. It aids in reducing the tolerance and errors before fabricating on a large scale. If any errors occur, the architects will redevelop the artifact (MARKS, 2016)/ (Ferschin et al., 2015).
- Assembly process: The assembly and subassembly regulations and instructions will be accommodated. The perspectives of DfMA are recognized as automation, simplification, automation, digitalization and flexibility (Tan et al., 2020b). Using digital design techniques will streamline the process of designing adaptable buildings. Finally, the design and fabrication quality can be evaluated in a real situation. These elements can be tested independently.

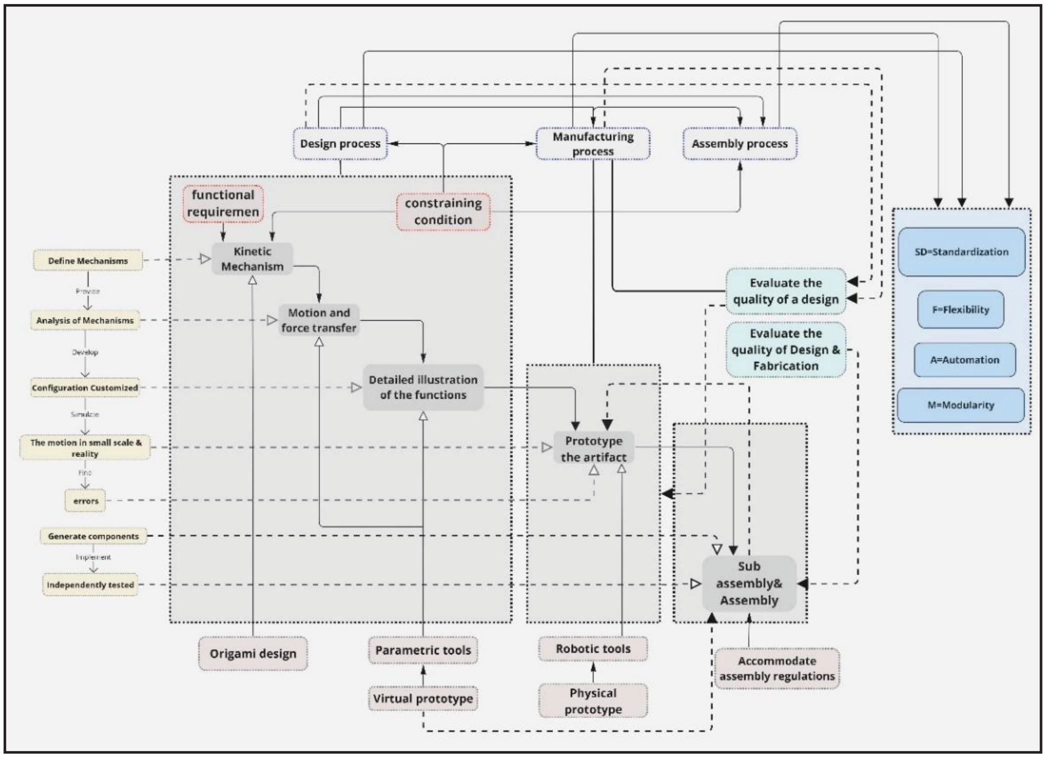

Figure 4.3 A Conceptual framework through digital design, Digital fabrication and DfMA, regarding the generation of adaptable elements

4.4.1 Implementation of framework in designing interior spaces

There are some steps to convert a mono-functional wall to the multifunctional wall. In the first concept, the dynamic openings are proposed. The first step includes studying the Control of Geometric Pattern Using a Digital Algorithm (with a Focus on the Analysis and Application of these modular patterns). This pattern consists of more than one shape that covers the entire wall and fills the space without overlapping or allowing gaps between shapes. The pattern consists of closed shapes and curves. The second step includes the Kangaroo plugin; forces and movement are used to create digital geometry that differs from classical geometry and also to analyze and control this pattern (Figure 4.4).

The adaptable permanent elements that are in interior and exterior space should be identified. These subdivisions are based on the modularity concept. Some items need to be implemented in designing the building. Transformation, position, connections, dimension and distribution can be addressed.

- Implement modularity in product and process: The independent sub-system can be recognized in this step. First, the permanent elements are selected. Second, the configuration of the building is chosen. Finally, the specific function is defined. This information is the input in parametric tools. For example, horizontal surfaces such as floors and pipes are extracted (Lennartsson & Björnfot, 2010).
- Optimize design: In this step, the cluster of elements can be generated. These clusters contain input icons. The icons relate to the size, length and width of the elements. The mathematics formulations can be used to generate the outputs (Knippers et al., 2021).
- Evaluate design: In this step, the artifact should be simulated by parametric tools for evaluation. Then, the functions should be analyzed. The following artifact design incorporates innovative features to create a versatile and adaptable interior environment.

The following is an explanation of the key elements:

- Movable Pattern on Transparent Wall: A transparent wall with a movable pattern is the objective of the design. This pattern serves two purposes: 1. Users can adjust the level of privacy within the interior space using the Privacy Control feature. In order to maintain privacy, occupants can manipulate the pattern to obscure or reveal the interior. 2. Control of transparency: The pattern also permits the users to control the transparency of the wall. Depending on the degree of transparency, users can control the amount of natural light and visibility on both sides of the wall.
- A modular repetitive element is incorporated into the design, which introduces a dynamic element to the interior space. It also has the potential of providing adaptability and using kinematic concepts as: Adaptability: These modular elements can be rearranged to quickly change an interior space's transparency. Various functions and activities can be accommodated by the space, depending on the needs of the user. Kinematic Concept: These elements utilize a kinematic concept that allows for smooth and controlled movement (Cudzik & Nyka, 2017). The concept ensures that

adjustments are effortless and precise, enhancing the user's experience (Moloney, 2011).

- Digital Design with Rhino and Grasshopper (Tedjosaputro, 2020)/ (Bazalo & Moleta, 2015)/ (Course of Architecture and Urbanism, Faculty of Engineering, Architecture and Urbanism and Geography, Federal University of Mato Grosso do Sul et al., 2016): An integral part of the design process is the use of digital design tools such as Rhino and Grasshopper. Some significant potential exists: 1. Visualization and Precision: These tools enable precise measurements, calculations, and design visualization. The movable pattern, modular elements, and their kinematic mechanisms are designed and aligned carefully by them. 2. Digital design facilitates iteration, allowing to refinement and optimization of the elements for functionality and aesthetics. Additionally, it facilitates efficient adjustments and experimentation during the design process.

The artifact design combines innovative features such as a movable pattern on a transparent wall, modular elements made of Voronoi, and a kinematic concept created using Rhino and Grasshopper. This design allow to creation a room that allows users to control privacy and transparency while the dynamic and user-driven changes to the layout (Figure 4.4). In Voronoi patterns, or Voronoi tessellations, a set of seed points is used to divide space into regions. All points within a given region are closer to their seed point than all other points within the region in Voronoi diagrams. It is possible for these boundaries to take on a variety of shapes and sizes depending on the distribution of seed points. They are arranged in n-polygonal shapes in this artifact. Consequently, the transparency of the wall surface will vary based on the Voronoi pattern. There will be less transparency in areas with smaller cells or regions, while areas with larger cells or regions will allow more light to pass through. The result is a visually dynamic and controlled transparency effect on the wall surface. To enhance the aesthetics and functionality of modular elements, Voronoi patterns can be incorporated into modular design concepts. The combination of Voronoi patterns and modularity allows designers to offer adaptable and customizable solutions that contribute to both the functional and aesthetic aspects of a space.

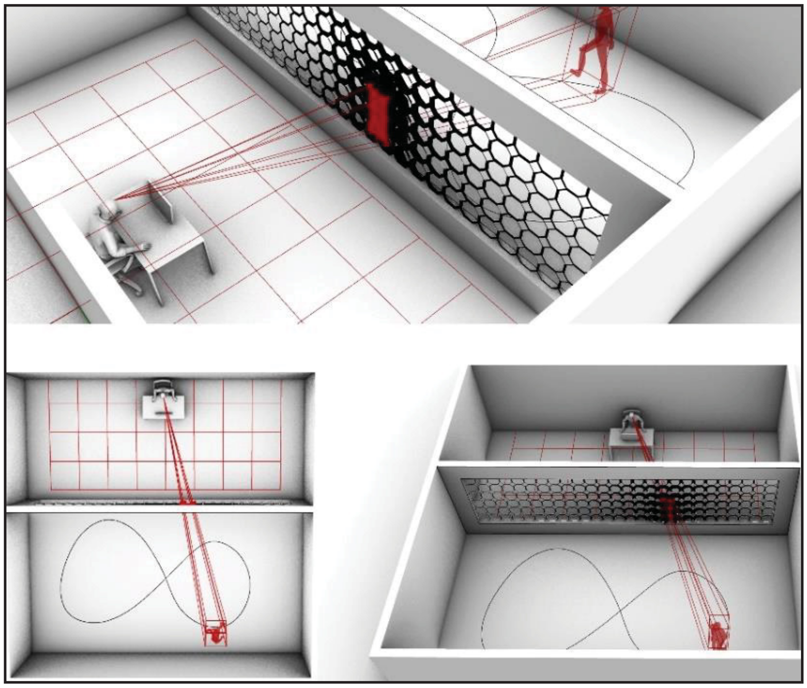

Figure 4.4 Dynamic Transparency: Adaptable interior Design with Modular Origami Elements

A transparent wall with a movable pattern offers users control over privacy and transparency within an interior space. It enhances the functionality and adaptability of the space by allowing occupants to adjust privacy and transparency levels. The modular origami-based elements with a kinematic concept enable easy reconfiguration of the interior layout. With Rhino and Grasshopper, the whole design process is driven by digital tools. As a result, this innovative artifact combines aesthetics, functionality, and adaptability to provide a dynamic and user-centric interior experience. Compared to traditional methods for creating adaptable educational buildings, the design approach presented in this project offers several advantages. Utilizing digital algorithms, parametric tools, and modular components enables high customization, efficient iterations, and precise control of elements such as movable patterns and modular components. This approach can achieve dynamic adaptation, user-driven layout changes, and efficient resource utilization. It provides a more dynamic and user-centric alternative to traditional methods for educational buildings.

4.5 Finding

The figure 4.5, illustrates a process for creating adaptable systems by applying various design and manufacturing principles.

System 1: Modularity

- Digital Design: This is where the initial digital conceptualization of the project occurs, focusing on creating designs that can be easily adapted or modified.

- Digital Fabrication: This is the application of digital technology to fabricate design components.
- Design for Manufacturing and Assembly: This approach focuses on designing components that are easy to manufacture and assemble, with the end goal of efficiency and cost-effectiveness.
- Design for Adaptability: This principle involves creating flexible designs that can adapt to changing requirements.

System 2: Enhanced Level of Adaptability: In the second system, the principles of modularity have interoperability with kinematic mechanisms (ME) and connection and joints which are vital for the physical realization of adaptive designs.

- Kinematic Mechanisms: These are the moving parts of the design that allow for the adaptability and flexibility of physical structures.
- Connection and Joints: These elements join the different parts of the design, which are crucial in ensuring the adaptive features for reconfiguration and adjustment.

Optimized DfAd: The outcome of integrating these principles and systems is an "Optimized Design for Adaptability," which suggests a refined approach to creating adaptable and efficient designs enhanced by the practical considerations of kinematics and connections.

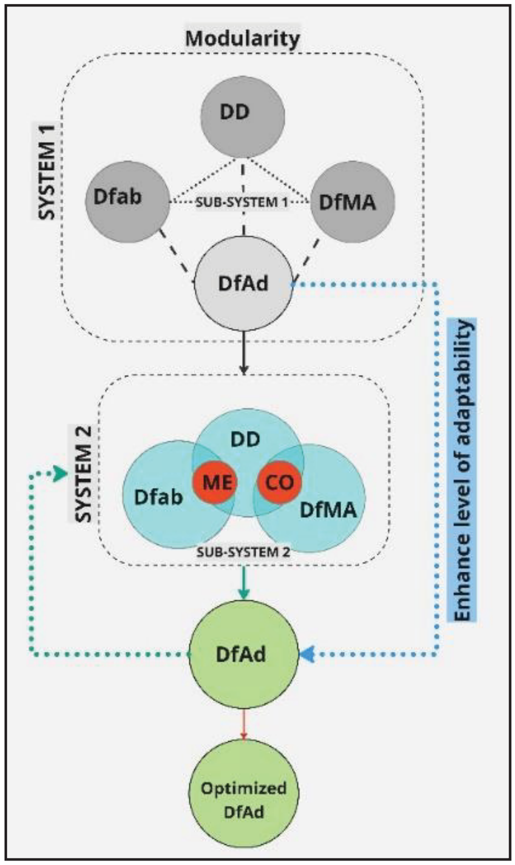

Figure 4.5 Modular, adaptable systems

It is possible to create two subsystems that work together within the larger framework using modularity. This modularity allows for individual components or subsystems to be developed, tested, and optimized separately before being integrated into the final, optimized system that emphasizes adaptability (Figure 4.6).

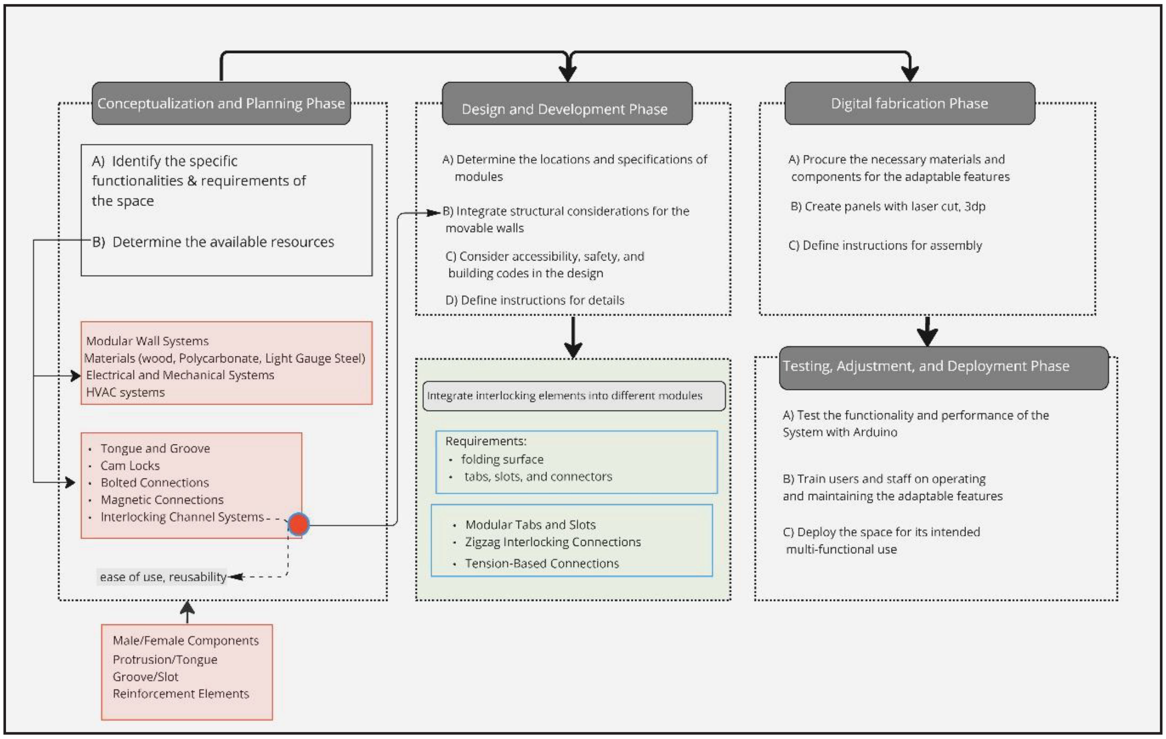

Figure 4.6 The structured process for creating adaptable spaces

The figure 4.7, outlines a structured process for creating adaptable spaces, proceeding through four key phases: Conceptualization and Planning, Design and Development, Digital Fabrication and Testing, Adjustment, and Deployment. Conceptualization and Planning Phase In this initial phase, the focus is on understanding the needs and limitations of the project. It involves identifying the specific functionalities and requirements of the space and determining the available resources. Resources might include modular wall systems made from wood, polycarbonate, light gauge steel, and essential electrical, mechanical, and HVAC systems.

Different types of connections, such as tongue and groove, cam locks, bolted connections, magnetic connections, and interlocking channel systems, are considered to ensure ease of use and reusability. Design and Development Phase: the next phase transitions into the actual design process, where the locations and specifications of modular components are determined. Structural considerations for movable walls and the design include the factors of accessibility, safety, and compliance with building codes. Instructions for intricate details are defined, ensuring all components work cohesively. Interlocking elements, such as folding surfaces, tabs, slots, connectors, modular tabs and slots, zigzag interlocking connections, and tension-based connections, are integrated into the different modules to facilitate adaptability. In digital fabrication after the design phase, the project moves into the digital fabrication phase, which involves procuring the necessary materials and components for the adaptable features, creating panels with advanced manufacturing techniques like laser cutting and 3D printing, and defining clear instructions for assembly.

Testing, Adjustment, and Deployment Phase: The final phase involves rigorous system testing, often utilizing technology such as Arduino to validate functionality and performance. Training is provided for users and staff to ensure they can operate and maintain the adaptable features effectively. Finally, the space is deployed for its intended multi-functional use, marking the culmination of the design and construction process. This framework illustrates a methodical approach to creating flexible and adaptable spaces that can be modified as needs change, leveraging modern digital fabrication techniques to enhance the precision and efficiency of construction.

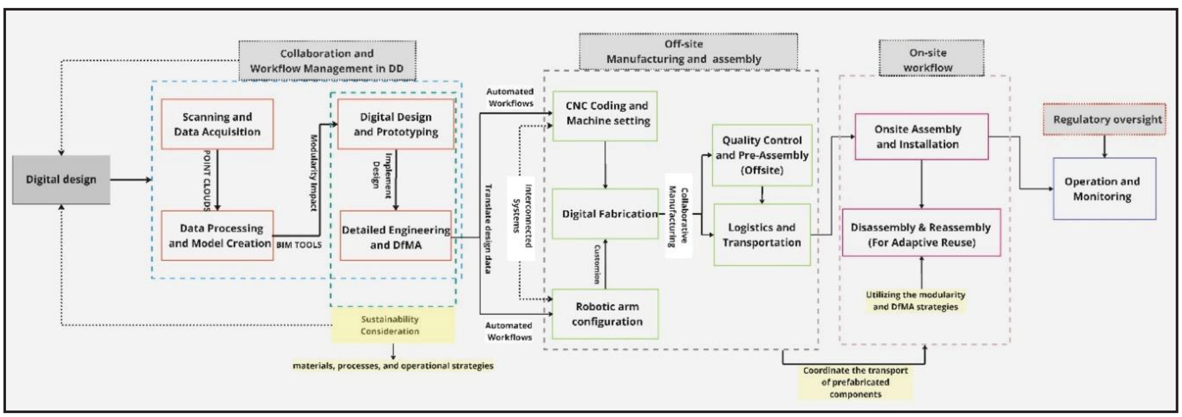

Figure 4.7 A comprehensive workflow for a Construction project through digital design and fabrication technologies

The image illustrates a comprehensive workflow for a construction project that utilizes digital design and fabrication technologies. The workflow includes several key stages, with each stage involving specific tasks and considerations:

4.5.1 Digital design phase

Scanning and Data Acquisition: This is the initial stage of collecting data, possibly through 3D scanning or other surveying techniques.

- Data Processing and Model Creation: The acquired data is processed to create digital models, likely using Building Information Modeling (BIM) tools. This stage is crucial for visualizing the project and planning its execution.
- Collaboration and Workflow Management in Digital Design
- Digital Design and Prototyping: This step involves iterative development and testing of the design.
- Detailed Engineering and Design for Manufacturing and Assembly: Detailed engineering takes the prototype to a higher fidelity, addressing the finer points of the design. DfMA principles are applied to ensure the components are easy to manufacture and assemble.

4.5.2 Automated workflows

CNC Coding and Machine Setting: Computer Numerical Control machines have the appropriate coding to produce the designed components.

- Digital Fabrication: In this stage, physical manufacturing occurs, utilizing digital data to control the fabrication machinery.
- Robotic Arm Configuration: Robotic arms are likely programmed and configured to perform specific tasks in the manufacturing process. Off-Site Manufacturing and Assembly include:
- Quality Control and Pre-Assembly (Offsite): Before being shipped to the construction site, the manufactured components undergo quality control and are pre-assembled

offsite to ensure they meet the required standards. Logistics and Transportation: The components are available on the construction site, which requires careful logistical planning.

4.5.3 On-site workflow

- Onsite Assembly and Installation: Once on-site, the components are assembled and installed into their final position.
- Disassembly & Reassembly (For Adaptive Reuse): The process also accounts for the potential future disassembly and reassembly of components, aligning with sustainable practices and adaptive reuse.
- Operation and Monitoring Phase:
- Operation and Monitoring: After the construction, the building enters the operation phase, ensuring that everything functions as intended.

The entire workflow emphasizes sustainability considerations and the use of BIM tools for design and project management. It shows a progression from concept to completion with a strong focus on digital integration, collaboration, and automated manufacturing while considering the constructed elements' ease of manufacturing, assembly, and future adaptability.

4.6 Real-world project application

This framework application addresses issues within an educational space, specifically the Pavilion FG at Concordia University (Figure 4.8). The problems, challenges, and solutions are in a table format, and the accompanying images appear to be architectural plans and representations of the spaces in question.

- First Image: This image likely shows a floor plan, with the "1" and "2" markers indicating key areas where the identified problems exist. "1" could represent the main entrance area, which is confusing due to its dual-use nature for educational and commercial purposes. The solutions proposed for this area include kinematic design elements, digital design and fabrication, and security measures to enhance clarity and flow for both types of visitors.

- Second Image: The second image seems to be a floor plan highlighting an area marked "3," which could correspond to the "Large & Useless Corridor" mentioned in the case study table. This area is noted as underutilized, contributing to flow disruption and energy inefficiency. The suggested solutions involve creating flexible connections, multifunctionality, and collaboration zones, transforming this space into a more vibrant and valuable area.
- Third Image: The third image provides a 3D layered representation of the building floors, indicating the areas of concern and their spatial relationship within the building. The highlighted issues are "Confusing Entrance" on the ground floor and "Underutilized Large Corridor" on the underground floor. The visual representation aids in understanding the spatial problems and the impact of the proposed solutions on these areas.

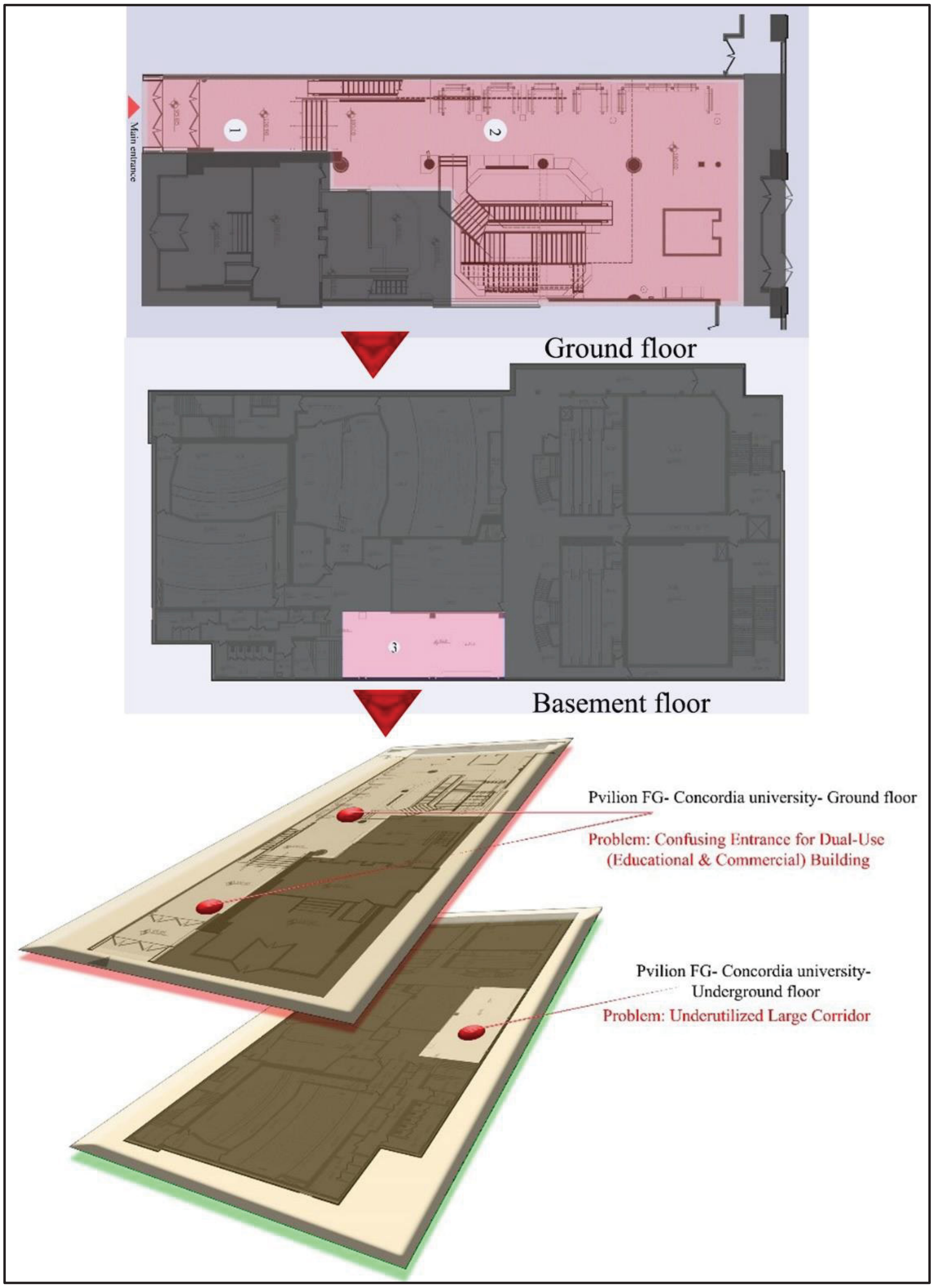

Figure 4.8 Two different floors of an
educational building of the case study

The case study presented in the table involves two primary areas of concern within an educational building: a confusing entrance and an underutilized corridor. Here are the key arguments supporting the need for adaptability in the 'corridor' at Concordia. First, the current state of the corridor as an underutilized space represents a missed opportunity in an educational environment where every square foot should contribute to the overall functionality of the building. By introducing adaptable design elements, the corridor can be transformed into a multifunctional area that supports variety of activities, from informal learning to collaborative work, making the space more valuable and dynamic. Moreover, an adaptable corridor can significantly improve the flow of movement within the building. As it stands, the corridor's lack of functionality disrupts the natural movement of people, leading to inefficiencies and congestion. Implementing flexible design features would allow the space to be reconfigured as needed, ensuring smoother traffic flow and better use of space during different times of the day or for various events. In addition to enhancing functionality, adaptability is crucial for fostering a more engaging and interactive environment. Currently, the corridor does little to inspire or engage those who pass through it. By incorporating elements that can change in response to different needs, the corridor can become a more vibrant part of the building, encouraging interaction, creativity, and collaboration among students and staff. Another important consideration is sustainability. The existing corridor likely consumes resources, such as lighting and climate control, without offering much in return. Adaptive design can introduce energy-efficient solutions and environmentally responsible materials, reducing the building’s overall energy consumption and aligning with broader sustainability goals. Finally, adaptability is key to ensuring that the corridor remains relevant and functional in the long term. As educational needs and teaching methods evolve, so too must the spaces that support them. By making the corridor adaptable, the university can ensure that it continues to meet the needs of future students and faculty, making it a sustainable and forward-thinking investment.

Table 4.1 Analysis of educational space issues

Area	Problem Description	Challenges	Solutions
Confusing Entrance	Dual-use entrance creating confusion for educational and commercial visitors.	1. Lack of Clear Indications 2. Traffic Congestion 3. Security Concerns	A. **Kinematic Design**: Adaptive facade, moveable partitions, transformable spaces. B. **Digital Design & Fabrication**: Interactive directories, digital signage, smart navigation. C. **DFMA & Modularity**: Prefab modules, flexible interior elements, scalable components. D. **Defined Paths & Zoning**: Distinct pathways, and symbolic design elements. E. **Security** F. **Hybrid Spaces**: Multi-use areas that can adapt based on time/event. G. **Post-Implementation**: User feedback, iterative design, technology upgrades. H. **Sustainable Design**: Green walls, enhanced natural light
Large & Useless Corridor	Underutilized and negatively flowing corridor space in the educational building.	1. Underutilization 2. Flow Disruption 3. Energy Inefficiency	A. **Flexible Connections**: Rotatable walls, sliding partitions. B. **Multifunctionality**: Learning pods, informal meeting spaces C. **Collaboration Zones**: Interactive walls, exhibition spaces E. **Technology**: AR/VR stations, digital displays F. **Sustainability**: Adaptive lighting, sustainable materials G. **Flexible Connection** H. **Events & Recreation**: recreational zones. I. **Acoustic Management**: Acoustic panels, thoughtful zoning J. **Artistic Elements**: Murals, student art K. **DFMA**: Modular, easily assembled furniture

For the Confusing Entrance: The problem is identified as a dual-use entrance that confuses educational and commercial visitors. Challenges include a lack of clear indications for different users, traffic congestion, and security concerns. The solutions proposed are:

- Kinematic Design: Implementing an adaptive facade and movable partitions to create transformable spaces.
- Digital Design & Fabrication: Using interactive directories and digital signage for navigation is practical.

- DFMA & Modularity: Development of prefabricated modules and flexible interior elements.
- Defined Paths & Zoning: Creating distinct pathways with symbolic design elements to direct traffic is essential.
- Security: Enhancements to ensure safety for all users.
- Hybrid Spaces: it emphasizes the design of areas that can change function based on time or events.
- Post-Implementation: Use of feedback for iterative design and technology upgrades.
- Sustainable Design: Integration of green walls and enhanced natural lighting.

For the Large & Useless Corridor: The problem is characterized by underutilized space, leading to disrupted flow and energy inefficiency.

Challenges are the corridor's underutilization, movement disruption, and inefficiency of energy usage. The solutions proposed are:

- Flexible Connections: This includes the installation of rotatable walls and sliding partitions.
- Multifunctionality: Creation of learning pods and informal meeting spaces.
- Collaboration Zones: Development of interactive walls and exhibition spaces.
- Sustainability: Adoption of adaptive lighting and sustainable materials.
- Events & Recreation: Designation of areas for recreational activities.
- Acoustic Management: Strategic placement of acoustic panels.
- Artistic Elements
- DFMA: Use of modular furniture that can be easily assembled or reconfigured.

4.7 Conclusion

In conclusion, this research has embarked on a journey to explore the integration of modularity and digital design principles in creating adaptable educational spaces and facades. A conceptual and practical framework grounded in modularity and digital techniques includes the investigation to apply the foundation for more adaptive and modular invention. The study has introduced two hypotheses: one focuses on the adaptability of building components like interior walls, and the other focuses on developing reconfigurable building systems. This research illustrates the definition of adaptability, the design of adaptable mechanisms, the construction of prototypes, and simulation. Based on the framework and the creation of these modular elements on the wall, users can dynamically adjust levels of transparency and privacy. In addition to using digital design tools such as Rhino and Grasshopper, these tools facilitate precise measurements, visualization, and efficient adjustments during the design process. This paper's research hypotheses and methodologies support the potential of modularity and digital design in creating adaptable educational spaces. The future work relies on the mechanisms designed in this study, specifically focusing on refining connections and structural principles within the origami-inspired and nature-inspired approaches. In summary, this research is a testament to the potential of modularity and digital design in shaping the future of educational architecture by addressing the challenges and consequences of not embracing adaptability. As a result, to refine and expand upon the findings, it aims to contribute to the evolution of adaptable learning spaces and their positive impact on education.

CHAPTER 5

INTEGRATING MODULARITY AND DIGITAL FABRICATION: A SUSTAINABLE FRAMEWORK FOR ADAPTIVE ARCHITECTURAL DESIGN

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Abstract

The growing need for adaptability in the built environment, driven by ongoing changes, has prompted significant improvements within the construction industry. Previous research indicates that modularity in the construction process enhances efficiency and safety. In addition, adopting innovative sustainability strategies addresses the industry's response to the transformative challenges and evolving needs of our built environment. Despite the rapid evolution of architectural design, there is a gap in integrating advanced digital technologies with established modularity principles. The primary challenge addressed in this paper is the static nature of conventional architectural designs that do not adapt to the dynamic needs of educational environments and lack circularity features. There is a tendency in traditional design practices to overlook the dynamic and evolving needs of educational environments, which can result in rigid and non-adaptive functions of the building. In addition, a gap was identified in the existing architectural research concerning the impact of modularity on adaptability and sustainability. Using Design Science Research (DSR), this paper proposes a novel framework integrating modularity, Design for Manufacturing and Assembly (DfMA), digital design, and digital fabrication to enhance adaptability and sustainability in educational architectural design. The operationalized theoretical basis is applicable by promoting efficient fabrication and assembly processes utilizing digital tools. Incorporating kinetic elements into the design of a building facilitates spatial adaptability. Using modularity in design facilitates the ease of assembly and disassembly, allowing spaces to transform from mono-functional to

multifunctional, accommodating a variety of uses and fostering adaptability. The evaluation involves the application of the theoretical construct to real-world scenarios to assess and refine its effectiveness and practicability to ensure that the artifact meets theoretical expectations and stands up to practical challenges. A transformative architectural model demonstrates a potential for significant improvements in space utilization and adaptability in educational design spaces. In conclusion, this research provides innovative insights into the body of knowledge in the field of educational architecture, and provides industry-specific actionable solutions, thus bridging the gap between theoretical research and practical implementation, proposing a potential strategy for educational environments to adapt to future challenges and needs.

Keywords: Adaptable architecture, Modularity, Digital Design, Kinetic architecture, Digital Fabrication, DfMA, Design of educational spaces.

5.1 Introduction

Through changing educational paradigms, versatile learning zones allow for various activities. Furthermore, better initial planning and systems can improve design projects of educational spaces by lowering the high maintenance, energy and temporary replacement costs (Emilia Plotka et al., 2016). Despite technological advances, traditional design practices fail to address educational environments' dynamic and evolving needs, resulting in rigid and non-adaptive structures (Scaradozzi et al., 2021). The ability of a building to adapt easily to changing needs and contexts is what makes it adaptive (Barozzi et al., 2016b). A building that adapts to its users' requirements can provide a range of functions with a particular objective (A. Elmokadem et al., 2019). According to Dovey and Fisher 2014, there are three critical aspects to educational learning spaces: a) exploring the possibilities for using common spaces, b) highlighting the adaptability of spaces with some more versatile ones, and c) arranging and connecting these spaces to facilitate diverse educational activities. Together, these strategies define the composition and adaptability of modern educational environments (Dovey & Fisher, 2014). According to Lanz and J (2022), adaptive reuse is a superior alternative to demolition and reconstruction. In addition to challenging widespread demolition, it promotes a more deliberate approach to urban planning and architectural design (Lanz & Pendlebury, 2022). This is an important consideration given that project managers and stakeholders often struggle with the amount of waste generated by traditional construction methods (Karthik et al., 2020). In addition, there is a lack of knowledge in creating virtual or physical forms of adaptive space, which indicates a need for additional research and development in this direction (Schulze & Pinkow, 2020). A lifecycle approach in adaptable building design aims to prolong building lifespans and minimize obsolescence, aligning with the Circular Economy's material reuse strategies, upcycling, and maintaining quality and efficiency (Askar et al., 2021).

The main principles of the Circular Economy (CE), which emphasize reducing, reusing, and recycling, have led to the development of products that can easily be disassembled for reuse. The modular construction increases the possibility for disassembly and reuse of building elements, thus improving efficiency and reducing waste. Aiming at CE, the use of the product is enhanced, its performance improved and its value increased (Thakker & Bakshi, 2021). Design for circular economies emphasizes adaptability and sustainability. In design for sustainability, circular material economies rely on quality material outputs resulting from refurbishment or recycling of non-reusable products (Teixeira Franca Alves et al., 2024). The primary challenge tackled by this research is the static nature of conventional architectural designs, which are unable to adapt to the fluctuating educational requirements and often lack sustainable features in the interior spaces.

This paper proposes a two-pronged methodological approach to address the problem: first, establishing a theoretical framework based on modularity, kinetic design, and Design for Manufacturing and Assembly (DfMA), and second, proposing an operationalization of this framework using digital design and fabrication. It leverages advanced digital tools to boost fabrication and assembly efficiency and precision. Our hypothesis is that implementing an integrated framework combining modularity, digital design, and digital fabrication during architectural design can help creating spaces that effectively respond to evolving educational needs and practices by enhancing adaptability through modularity and kinetic design.

5.2 Literature review

In recent years, the interest towards adaptability has increased due to its ability to create diverse and user-specific environments. Due to its ability to adapt to changing circumstances, the design of educational spaces can contribute to sustainability and reusability. This literature review focuses on the following subjects, starting with some definitions: building's adaptability, the use of digital technologies, innovation in construction, and the application of modularity and DfMA in construction.

5.2.1 Adaptability

In nature, adaptability is an essential characteristic for survival. It is possible to extend this concept to architecture, where it transforms buildings from static structures to dynamic organisms that can respond to external and internal needs for changes.By utilizing modular components, buildings can be made more sustainable and reusable, allowing individual parts to be replaced and allowing them to evolve and expand over time. In addition to accommodating a variety of lifestyles and living habits, this adaptability also facilitates extendibility and personalization (Kai, 2022).

Adaptability in architecture refers to a building's ability to adapt to its surroundings, thus improving its long-term value. Architecture includes adaptability, which involves both the adaptation of the building by its users and the modification of the building itself in response to the changing environment (Kamara et al., 2020). Design for adaptability refers to the ability to establish basic system configurations that allow the expansion or contraction of functional areas while remaining within the limits of existing fixed constraints. Adaptability involves designing flexible and modular systems, allowing for adding new features or functions without requiring a complete overhaul of the existing system. It also requires anticipating future needs and planning system changes accordingly (Gosling et al., 2008). The definition of adaptive systems varies, with terms like 'kinetic,' 'retractable,' and 'adaptive.' (Barozzi et al., 2016b).

The study of motion without considering mass or force is called kinematics (Barozzi et al., 2016b). Kinetic architecture involves designing buildings or systems with mechanical elements that transform. Many technical choices aid in implementing this strategy, using the number and kind of actuators and the form and function of mechanisms (like Arduino) as a part of the movement and digital tools to present the process of kinematic characteristics. The study of force-induced motion in objects is dynamics (Barozzi et al., 2016b). An adaptive design can adapt a building's volume or internal structure to changing uses and space requirements (Belyaeva, 2017). Convertible buildings are designed for multiple uses, requiring internal and external alterations. Special attention is given to managing large spaces, using renewable materials, and designing open areas to support these diverse functions (Anupa Manewa et al., 2013). The term transformable is similar to the word convertible and refers to a controlled change in structure (Barozzi et al., 2016b).

Architectural movement and transformable structures can change geometries repeatedly and reversibly in response to environmental conditions and occupant requirements (Maden, 2019). A responsive system actively reacts to changes rather than being controlled externally. The responsiveness of contemporary adaptive architectures helps use mechanical and electrical components that provide the capability of sensing, analyzing, controlling, and operating (Holstov et al., 2017). The consideration of movement is a significant factor in designing for adaptability. Architectural planning based on Design for Adaptability (DfAd) takes into account the potential future ease of adaptation to changing needs and environmental conditions over time. Askar (2021), stated that adaptability is a critical facilitator in creating circularity in building practices, emphasizing the principles of open building and shearing layers. Due to their adaptability and ability to customize "fit-out" configurations, building products and materials can be reused. Design for adaptability considers building obsolescence and redundancy from a lifecycle perspective (Askar et al., 2021).

5.2.2 Sustainability through modularity

Developing modular system architectures reduces complexity and improves coordination. By combining modularity with effective teamwork, this approach addresses design challenges while balancing interdependence and coordination. Modular designs effectively manage complexity in large-scale projects using standardized components and off-site construction (Tee et al., 2019). Due to its speed, cost-efficiency, and lower ecological impact, modular construction is becoming a trend (Hořínková, 2021), as it is praised for its efficiency, cost-effectiveness, and reduced environmental waste material (Egege, 2018). The synergy between modular construction and digital design technologies contributes to a broader objective: advancing architectural practices to meet the immediate demands of adaptability and precision while aligning them with long-term sustainability goals.

By integrating these innovative methods, the architecture and construction fields have less ecological impacts while promoting economic and social well-being, illustrating a comprehensive and forward-thinking approach to sustainable development in the built environment. For instance, by incorporating kinetic facade systems into building envelopes, the building envelopes can adapt dynamically to environmental conditions and maximize occupants' comfort through natural heating, cooling, and lighting thus reducing reliance on traditional systems. Kinetic, responsive materials further simplify and enhance such adaptive building skins (Holstov et al., 2017).

An analysis of cutting-edge developments in assessing the environmental impact of digital fabrication emphasizes the importance of material efficiency and the integration of multiple functions (García de Soto et al., 2018). Sustainability in digital fabrication involves the use of recyclable materials, the efficient use of tools, and waste reduction. Through digital manufacturing, designers and contractors contribute to sustainable production by emphasizing product reuse and the use of local materials (Soomro et al., 2021). In terms of architectural design, transformable structures, as an example regarding sustainability and adaptability, are revolutionizing the field by offering rapid adaptation to environmental changes, combining functionality with innovation to meet diverse needs in various environments. Climate-adaptable structures, such as convertible roofs, quickly adapt to changes in weather conditions. Through a combination of flexibility and rapid environmental responsiveness, these structures provide natural lighting and ventilation.

5.2.3 Digital design and digital fabrication for adaptability

In creating adaptable spaces and designing for adaptability (DfAd), digital design can provide precision, efficiency, and flexibility unmatched by traditional design methods. Digital design can be performed using various methods and tools, like building information modelling (BIM), generative design, computational design and parametric design. BIM systems combine regulations, procedures, and technologies to create a "digital representation of the project," which can be formatted digitally and managed throughout the project lifecycle (Ma et al., 2021b). As an approach to digital design, generative design involves collaboration between designers and computer algorithms. The algorithm can handle large data sets, generate various outcomes, and identify optimal solutions through this process. It involves iteratively refining a computational model and design goals and automatically generating design alternatives to enhance understanding and decision-making. These strategies in designing building components with kinetic features have some impacts, such as conforming to architectural, spatial, functional, and structural performance requirements, incorporating affordable mechanisms in an appropriate place, and transforming with a designed geometry. A kinetic system is capable of performing multiple functions within a single structure. This technique can make buildings more resource-efficient and adapts to various site conditions and functional requirements.

This system is fundamental in an industry increasingly conscious of environmental responsibilities (Phocas et al., 2012). Generative Design (GD) and Building Information Modeling (BIM) transform intelligent design. From creative design problem-solving to comparing software and programming methods in tool development, BIM can enhance GD's efficiency (Ma et al., 2021b). In addition, computational design combines functionality, efficiency, aesthetics, and simplicity through algorithmic thinking, which links design intent to outcome. For problem-solving, algorithms aid in considering various factors, like structural systems. Architects, structural engineers, and urban designers use generative design systems to reach sub-systems, mainly for sustainable architectural applications, such as daylight maximization and energy efficiency. Generative design is also recognized as a critical tool for architects and engineers, enabling the development of sub-systems specifically designed to enhance energy efficiency and maximize daylight in buildings (Wojtkiewicz, 2014). By using tools like Grasshopper and Dynamo, architects can transform design parameters into automated algorithms. Parametric design involves defining variables and using computational methods to generate multiple solutions. Instead of creating fixed solutions, this approach emphasizes relationships within the system. In addition to being effective at quickly producing and modifying designs, it helps to understand how different elements affect the visual and spatial outcome. Digital design reduces design time, improves quality, increases efficiency, increases the diversity of design solutions and automatically eliminates inappropriate possibilities (Smorzhenkov & Ignatova, 2021). Digital fabrication plays a crucial role in designing for adaptability, enabling spaces to be easily modified or refreshed in response to evolving requirements.

The preferred method for developing and testing the design is prototyping with digital fabrication technologies. These technologies allow for the digital design of the prototype in a digital environment, followed by its creation using computerized equipment (Soomro et al., 2021). Arduino has enabled practical applications in interactive design prototypes through generative and parametric design, scripting, real-time data analysis, electronic prototyping, and digital fabrication. Arduino bridges the digital and physical worlds and simplifies data collection, making it a standard tool in design. With Arduino, sensors woven into fabric surfaces can continuously provide data to the design environment. Connecting different components to the breadboard is simple, making testing and debugging the circuit easier before committing to a more permanent design. (Peters et al., 2013).

5.2.4 Synthesis of the literature review and identified gaps

The literature review highlights the advantages of digital design methods, such as computational and parametric design, in the creation of adaptable spaces. Digital fabrication has a crucial role in design for adaptability. A digital fabrication process can use data-driven design approaches to manufacture products. The design of buildings with moving elements, known as kinetic architecture, has gained popularity due to technological advancements. In addition to precision, efficiency, and flexibility, these digital approaches contribute to the transformation of traditional design and construction processes. Material consumption can be reduced by extending the lifespan of components. Adaptability and flexibility are often associated with standardization and modularity in the construction industry. (Minunno et al., 2018). In addition to combining different components within a system, modularity has also been recognized for its ability to be adaptable, responsive, and versatile to meet a range of requirements. The identified gaps include a lack of discussion on integrating these methods, a limited focus on user-centric design, and the need for scalability and accessibility for various project sizes. Furthermore, these approaches have not been validated with real-world case studies. Also, dynamic facades can adjust their position to maximize solar gain or reduce wind load, contributing to the building's energy efficiency and sustainability. By leveraging advancements in materials, technology, and design, architects and engineers can create buildings that are not only more efficient and sustainable but also more responsive and adaptable to the needs of their occupants and the environment. However, addressing the challenges associated with cost, complexity, and maintenance will be essential to realizing the full potential of kinetic architecture in the future.

5.3 Objectives and Methodology

The main objective of this study is to propose a framework for building's adaptability through modularity, digital design, and digital fabrication. The Design Science Research (DSR) methodology is adopted as it addresses a real world problem (as it is in the case of this study), aims at designing and implementing information systems scientifically (De Sordi, 2021), and brings contributions to both science and practice. According to this methodology, the research is structured into the following steps:

1. Problem Identification: This research begins by acknowledging the current educational spaces' inflexibility and environmental shortcomings, which fail to meet users' evolving needs and requirements.

2. Literature Gap Analysis: The literature review (section 1 of this paper) emphasized the lack of a theoretical or practical solution addressing adaptability by incorporating modularity, digital design, and digital fabrication.
3. Development of an ‘artifact’ aiming at solving the practical problem and bridging the literature gap: Development of a theoretical framework integrating modularity with kinetic design and Design for Manufacturing and Assembly to provide for adaptability of the architectural design.
4. Demonstration of the artifact: Operationalization and application of the framework: This step involves translating theoretical concepts into practical design processes, thus, utilizing the proposed framework to operationalize adaptive building strategies within educational buildings.
5. Evaluation: Based on a real project application, this methodology evaluates the adaptability, and the impact of dynamic modular wall systems in educational settings.
6. Analysis and Validation: it involves examining and assessing of the practical applications and refining the framework in response to feedback and outcomes, thus enhancing the body of knowledge and providing industry-specific solution.

As part of DSR, formative evaluations can improve the characteristics or performance of the subject through empirically based interpretations that guide successful actions. Formative evaluations, which aim to iteratively improve a design artifact and its application before finalizing the solution, involve evaluating dynamic, modular wall systems in educational settings and then analyzing and refining the framework based on feedback and outcomes (Venable et al., 2017), which can be the case of our proposal too.

5.4 Framework for design for adaptability through modularity and DfAd

In the dynamic and rapidly evolving field of architecture and construction, integrating advanced technological methodologies and innovative design principles is a trend and a necessity. Based on the results from the literature review, this framework integrates DfMA, modularity, and digital design and fabrication.

5.4.1 Theoretical bases of the proposed framework

As discussed in the literature review, DfMA utilization emphasizes the ease with which components can be manufactured and assembled. Construction processes can be streamlined and made more efficient by integrating DfMA into modularity. This part of the framework includes various innovative concepts, such as Design for Disassembly (DfD), Design for Assembly (DfA), and Design for Reusability (DfR), each focusing on a different aspect of the construction lifecycle. On the other hand, modularity in design refers to dividing a system into smaller parts or modules that can be independently created and used in different systems. This approach offers significant benefits in adaptability, cost-effectiveness, and sustainability. Modular designs create visually stimulating spaces that are highly functional and easily adaptable as needs change (Nakib, 2010). The integration of digital design further enhances the modularity aspect. As a result, advanced software and tools can precisely design modules to ensure their perfect fit in the final construction. It is also possible to explore unique design concepts through digital design, including origami-based techniques for folding and unfolding structural elements quickly, fractal geometries for efficient material utilization, nature-inspired pattern analysis for aesthetic enhancement, and kinematic integration for dynamic and functional design solutions (Kolarevic, 2003)(Belma & Sonay, 2016). Modularity concepts can accommodate design changes and adapt to architectural requirements and client preferences.

In the proposed framework, digital manufacturing combines digital technology with traditional fabrication processes. As a result of this, the digitally designed modules are manufactured offering high precision and customization capabilities. By using digital fabrication techniques, such as 3D printing, CNC machining, and laser cutting, architectural elements that would otherwise be difficult, if not impossible, to produce can be created (Kaiser et al., 2019). The use of digital fabrication in architectural design has profound implications. This approach allows for greater design flexibility and optimization of each module or component for performance, aesthetics, and sustainability. Mass customization becomes a reality as digital fabrication produces unique, tailored elements that meet client and site-specific requirements.

5.5 A Comprehensive framework for future-ready architecture

Combining modularity with digital fabrication, the proposed framework (Figure 0.1) aims at offering a holistic strategy for interior space and facade design and construction. The framework is composed of several modules, each of them highlighted in a different color in the figure. The following sections explore each module in broader depth, examining their components, benefits, and practical applications. It proposes a paradigm shift in thinking about designing and building spaces. The first block of the Framework: ‘Requirements and strategies specifications’ consists of three steps. The first one is ‘Input’, such as customer needs, dimensions, and requirements. Some general strategies are taken in consideration from the very beginning of the project: modularity, digital design, mass customization, and DfMA, aiming at reducing waste and enhancing precision during assembly (Tan et al., 2020b). General and also specific design strategies complete the first block of the Framework.

As specific design strategies to achieve adaptability through modularity: origami-based techniques, fractal geometries, natural patterns, and kinematic integration to achieve effective material utilization and dynamic design can be used. To ensure spatial flexibility, designers may incorporate movable components into their design. This movability emphasizes the dynamic nature of reality in time, a feature that can continue to develop as education practices advance (Scaradozzi et al., 2021). With increasing interest in evaluating modular designs for high-rise building facades, architects have used origami to create modular and adaptable structures (Joshua Schultz & Neil Katz, 2018). Joshua Schultz and Neil Katz's 2018 research often focuses on the modularity of origami elements rather than integrating them into a complete building system.

In the case of the Beijing Greenland Tower, a foundational case includes a flat wall, followed by studies on the solar exposure of various modular origami units. A direct relationship was observed between the extent of protrusion and the glass angle, indicating that modular design impacts self-shading (Joshua Schultz & Neil Katz, 2018). As for technology placement and modular design, the strategy emphasizes reusable components, easy maintenance, and recyclable materials. With the development of technology and modularity, it is increasingly possible to produce and operate products that are adaptable, interchangeable, durable, and recyclable. A durable product can last for a specific duration, but not longer, so it can still be adapted to meet the specific needs of the end user (Teixeira Franca Alves et al., 2024).

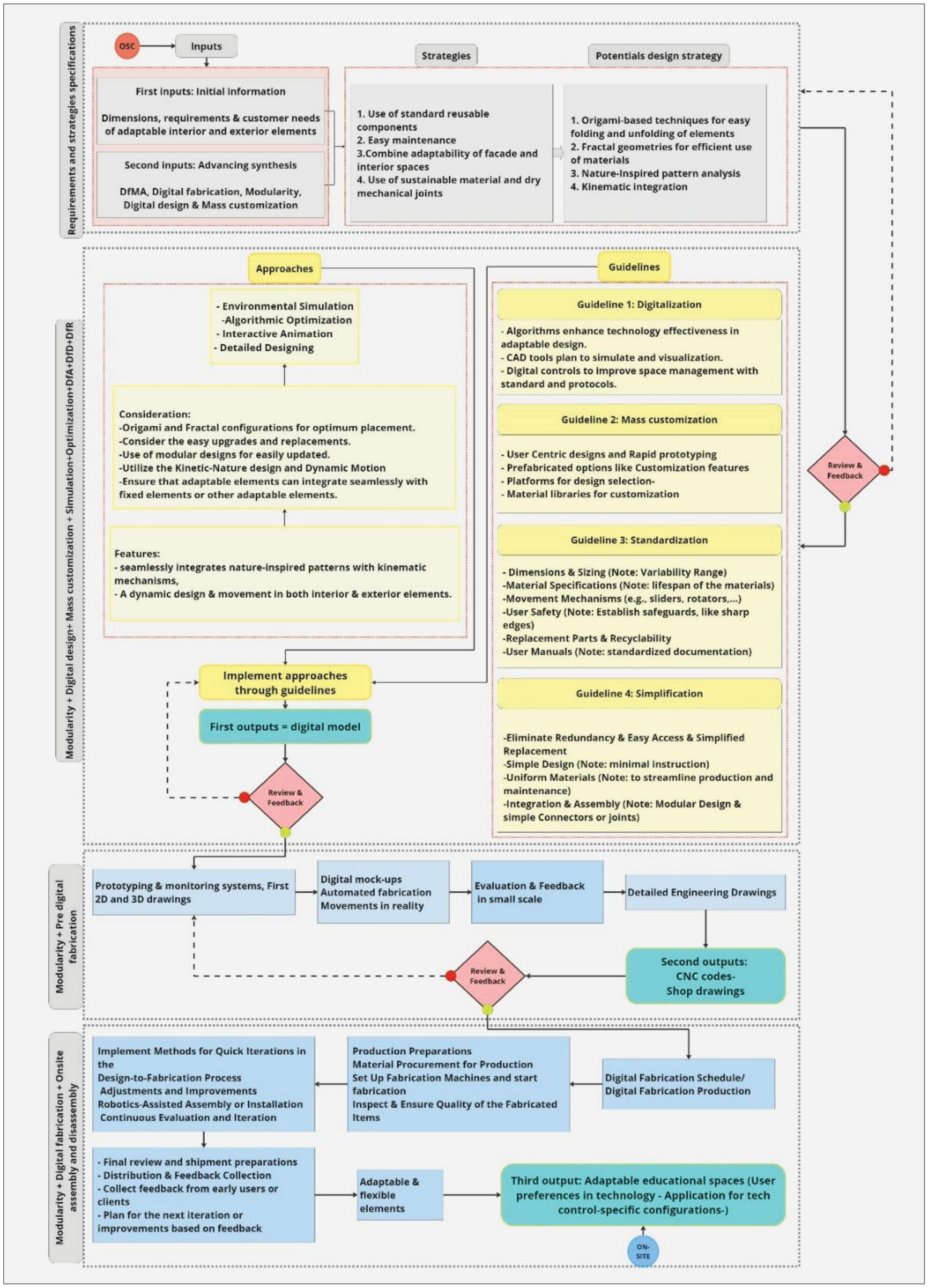

Figure 5.1 Proposed Framework for Design for adaptability through Modularity and Dfab (FDA-MDF)

The ‘Review and Feedback’ action (indicated by a rhombus with a yes/no output) provides possibility for iteration or leads to further development through digital modelling, mass customization, environmental simulation, algorithmic optimization, and interactive animations. The next large block includes digitization, mass customization, standardization, and simplification to ensure user-centric design, and efficient production methods. This phase aims to create a dynamic artifact integrating nature-inspired patterns with kinematic mechanisms. Kinetic design requires an interdisciplinary approach across architecture, mechanical, and structural engineering. In architectural design, kinetic functionality introduces dynamic components such as joints and mechanisms.

Afterwards, the framework moves to fabrication and detailed engineering preparation, involving prototyping, digital mockups, and automated fabrication processes. Integrating adaptable elements seamlessly with fixed components is ensured by quality control. For efficient production, the final phase is digital fabrication, which uses automation and digitalization. The process includes setting up fabrication machines, ensuring quality, implementing quick design iterations, and utilizing robotics-aided assembly. A final review, distribution, feedback collection, and planning for subsequent improvements conclude the process. The implementation of this framework could allow educational spaces to be adapted and flexible according to user preferences and configurations.

Through digital fabrication, spaces can meet the unique needs of their users. Adding quantitative measures, such as productivity metrics, would enhance future research and assist users in making better decisions. In addition, sustainability factors, as well as the resources needed for the process, the final product, and the link between manufacturing and product, should be more thoroughly incorporated into evaluation systems (Graser et al., 2021). In summary, the proposed framework has the potential to contribute to greater adaptability of educational buildings in the following ways: By integrating digital fabrication and modularity, the framework enables greater efficiency and precision in using materials and resources. The expected result is a reduction in waste and an improvement in the quality of the final architectural product to design educational spaces and meet changing needs. With this adaptability, the designs can be more sustainable over time, aligning with the dynamic nature of the contemporary architecture. A sustainable approach includes the concentration on recyclable materials, flexible connections and efficient design, so the framework contributes positively to the sustainability of the environment. The design of sustainable systems must also be flexible enough to accommodate changes in circumstances. Design flexibility is essential to adapt to a dynamic world with changing needs and technical objectives (Teixeira Franca Alves et al., 2024). Additionally, the adoption of dry connections is crucial to the design of a sustainable and adaptable building. Interlocking joints and modular systems facilitate easy assembly and disassembly (Zhang & Balkcom, 2020). A broader range of applications is possible with this framework due to its combination of user-centric design, digital tools, and adaptable structures (Nakib, 2010).

By integrating user-focused design, digital technology, and adaptable structures, the framework ensures that the built environment meets its occupants' evolving needs and preferences. The framework aims to create functional, comfortable, and accessible environments by engaging directly with users, leveraging digital visualization tools such as BIM and designing flexible spaces that can be reconfigured over time. It ensures both user satisfaction and the long-term relevance and value of buildings, aligned with sustainable architectural practices. User comfort, functionality, and engagement incorporate feedback mechanisms, simulation technologies, and modular design elements. In summary, the framework integrates modularity with digital fabrication, focuses on sustainability, and emphasizes user-centric design. As a result, architectural designs are expected to be more efficient, adaptable, and aligned with current technological and environmental trends.

5.6 Operationalizing theoretical frameworks in adaptive building design

According to the DSR methodology, the proposed framework should be evaluated to determine to what extent is satisfies the initial objectives of this study. Two processes are used for this evaluation: one for new construction and one for existing buildings. Accordingly, in the proposed operationalization of the theoretical framework (Figure 0.2), the first step whether for an existing structure or a new construction, is to utilize digital design and documentation tools to conceptualize, plan, and prepare for the design implementation. In this process, the project’s context sets the stage for all subsequent actions and decisions. When it comes to existing buildings, it is essential to accurately capture their current state and identify the best ways to integrate new designs offering future adaptability. The new construction process involves starting from scratch and optimizing the design to ensure meeting future needs. It also takes advantage of new technologies and materials. In both scenarios, the goal is to create a functional, sustainable, and adaptable space to meet current requirements while allowing for future growth.

5.6.1 In an existing building

Digital design and documentation for existing buildings involves understanding and documenting the current state of the building before designing it. Typically, it involves:

- Assessment and Surveying: To create an accurate model of the building, detailed surveys, including 3D scans, are conducted. Understanding the existing structure's limitations and opportunities is crucial.
- Structural Analysis: The current structural integrity and layout are analyzed to determine whether the proposed changes or additions are feasible. This analysis includes understanding the load-bearing walls, the electrical layouts, the plumbing, and other critical infrastructure components.
- Retrofitting Strategies: Considering the current state of the building, strategies can retrofit the building with new technologies or design elements. Adding new features or updating systems can improve efficiency, accessibility, and space utilization.
- Preservation and Compliance: It is vital to consider preservation requirements and local building codes and regulations when working with existing buildings, especially those that are historic or have some architectural significance.
- By facilitating updates to existing products after implementation, the Integrate Technological Advances principle reflects design aspects; modular design, for instance, could allow plug-and-play modules for new technologies over time (Teixeira Franca Alves et al., 2024).
- In new construction

New constructions begin at conceptual stage and have greater flexibility in terms of design and implementation. As part of the digital design and documentation process, the following steps for digital design considerations are:

- Conceptual design: The process involves brainstorming and developing initial design concepts based on the client's requirements, the intended use of the building, and the site's characteristics.
- Architectural modelling: BIM or CAD software aids in modelling detailed architectural models. As a result, it is applicable to test the different design scenarios and adjust before construction begins.
- System Integration: It includes integrating various systems, such as HVAC, electrical, and plumbing, into the design of the building. It is possible to design these systems to be more efficient and integrated from the beginning when designing a new building.
- Building Codes and Regulations: Ensure that all parts of the design follow the building codes and regulations. New constructions must meet safety, accessibility, energy efficiency, and other standards.

Both scenarios require digital tools to produce detailed documentation that guides the construction process. In existing buildings, the emphasis is on adaptation and integration, while in new construction, the focus is on innovation and optimization from the ground up. Figure 2 represents the "Operationalized Framework for Adaptive Building Design" and gives a comprehensive overview of the various phases of designing, developing, and implementing adaptive building projects. It comprises of five phases, described in what follows:

1. The initial design (pre-design) and design development phases: In this step, DfA and DfD aspects aid in creating modular components with assemblable and disassemblable components, which is crucial for adaptable building design. During the design development phase, uning Design for Manufacturing (DfM) strategy helps creating detailed components suitable for manufacturing processes, ensuring that components are efficient. Design for Reassembly (DfR) refers to designing buildings and components to be easily disassembled and reassembled. Reusing and reconfiguring

materials and structures is especially relevant to sustainable development and the circular economy, which can significantly reduce the use of resources and waste.

2. Data management: During the pre-design phase, data acquisition, processing, and sharing are crucial for the project's success. Various formats and software can help manage the various data types, such as PDFs, BIM files, point clouds, and ortho-mosaic maps. In post-processing, tangible and intangible outputs, such as digital data files and quality assurance information, are managed.
3. Digital fabrication: During the design development phase, it is essential to consider the programming and configuration of the digital fabrication utilities. Material setup and machine setup are part of this process. The post-processing phase contains tangible results, where fabricated components and assembly fixtures aid digital fabrication.
4. Off-site preparation and logistics: In this case, the off-site artifacts include the pre-assembly of components, which involves the sorting of materials and components, packaging, and documentation subject to quality control before shipment.
5. On site activities: Refers to the assembly and disassembly of the site, the integration of utilities, and the provision of instructions for use and maintenance. During this phase, the building components are constructed and utilized; the adaptability is put into practice.

Several indicators for Quality Control (QC) are present in the flowchart, emphasizing the importance of maintaining quality throughout the process. This chart illustrates the multifaceted nature of adaptive building design by integrating various disciplines and technologies. Unlike being linear, this process involves iterative feedback loops through which insights and data from one phase inform adjustments made in the next. Quality control is in all stages of the adaptive building design process, from data acquisition to component installation. The significance of operationalizing framework in adaptive building design lies in its ability to systematically translate theoretical concepts into practical applications. The following are some of the potential benefits of this approach:

- Design Theories: Bridging the gap between abstract design principles and real-world construction practices is achievable through theoretical aspects of adaptability and sustainability in building design.
- The process can be efficient by following a structured approach, thus reducing errors and rework risks. This systematic methodology can reduce costs and optimize time throughout the project lifecycle.
- Collaboration is improved: The framework facilitates better communication and collaboration between all parties involved, including architects, engineers, contractors, and clients.
- By using digital tools and focusing on adaptability, the framework encourages innovation in design and construction techniques, which results in more flexible and future-proof buildings.
- Enhances Quality Control: The emphasis on quality control at every stage ensures that the building meets design and functionality requirements and safety standards.
- Adaptability supports sustainability by promoting efficient use of resources, minimizing waste, and allowing the building to change over time without extensive reconstruction.
- The framework provides a roadmap for decision-making, which is instrumental when dealing with complex projects that must consider various factors and constraints.
- This framework ensures documentation of each step of the process and transfers or uses it for future projects, creating a repository of best practices.

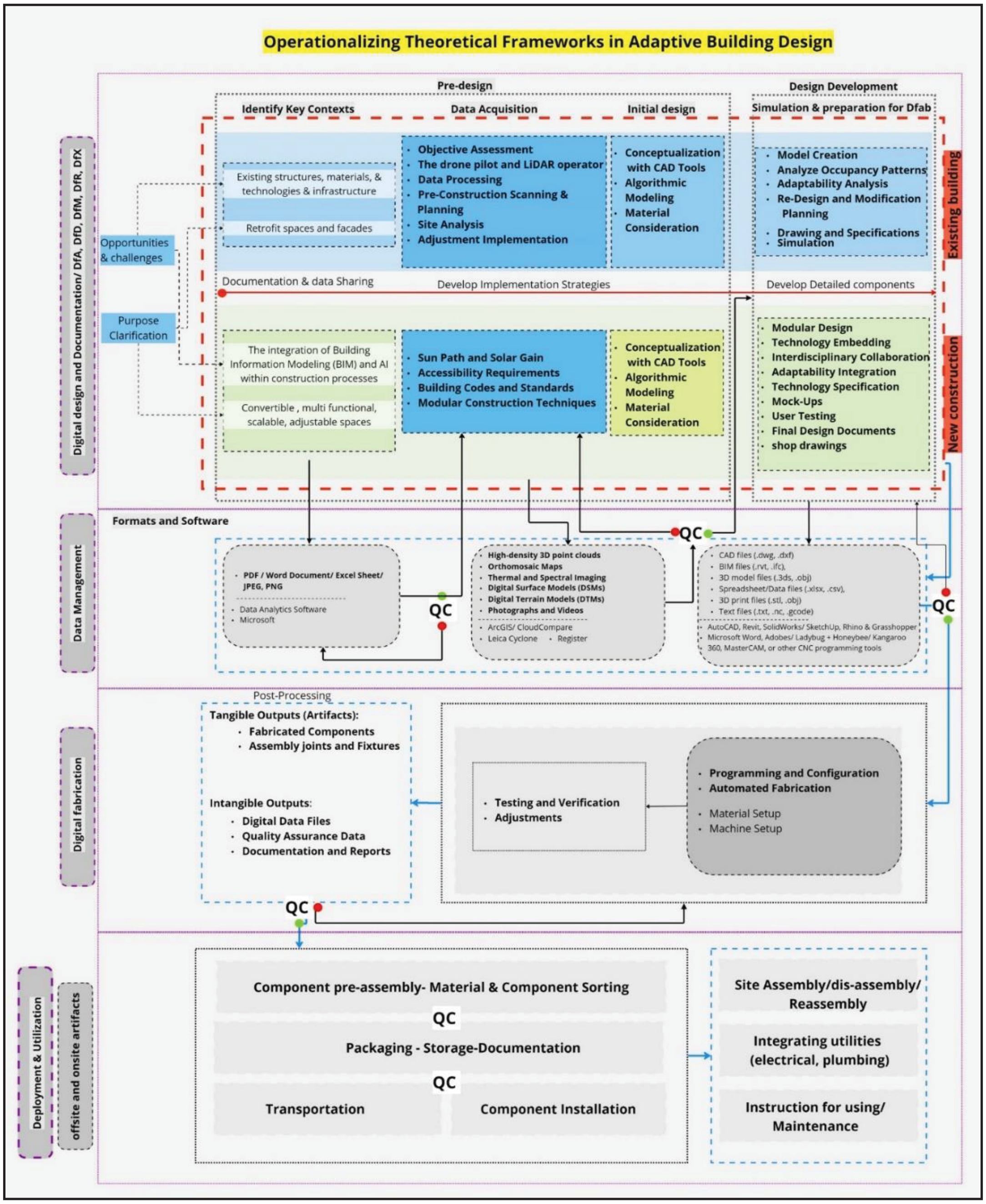

Figure 5.2 Operationalizing of the Theoretical Framework

5.7 Evaluation - Dynamic Modularity in adaptive wall systems

Following the proposed framework and its operationalization, this real case application aims to demonstrate the innovative digitally designed adaptive wall system within an educational setting. It uses digital design tools, CNC laser cutting fabrication, and Arduino-driven kinetic functions. A biomimicry-based series of interconnected wall modules demonstrates how parametric design and digital fabrication techniques can offer adaptability and functionality of educational interiors. In Figure 3, an adaptable wall is inspired by the functioning of a scorpion's tail. This innovative concept combines kinematic movements and parametric design principles with functionality and aesthetics. The following is a comprehensive explanation and analysis of the artifact:

1. Functionality and adaptability

- Biomimetic mechanism: This mechanism simulates the movement of a scorpion's tail, which can collect, close, and then reopen. In this way, the artifact can dynamically transform space to meet the needs of its users.
- The division of space can be quickly adapted in educational buildings or similar environments so that different areas are ready for different activities or functions.
- Aesthetics and Design
- Nature-inspired pattern: Design cues derive from natural forms and structures, providing aesthetic appeal, strength, and flexibility.
- It includes parametric modelling, which allows complex shapes and forms to be easily adjusted or scaled based on specific requirements.
- Digital fabrication and DfMA: Design for Manufacturing and Assembly principles indicate that fabrication of some components is applicable off-site to ensure a quick and efficient on-site assembly process.

2. Modularity

- The design comprises units and service availability in various configurations, and the system can be scalable and adaptable to various spaces and functions (Anupa Manewa et al., 2013).

- Modular design: Due to the artifact's modular structure, it can be retrofitted into existing buildings, allowing for the redesign of spaces without requiring significant structural modifications.

3. Kinematic movement and technical aspects

- Dynamic Configuration: The artifact's kinematic movement allows it to move and reconfigure, changing the shape and size of the enclosed area (Phocas et al., 2012).
- Innovations in mechanical design: The design incorporates joints, hinges, or other mechanisms that facilitate smooth movement, like the joints in a scorpion's body.
- Electrical Integration: The two-layered and parallel arrangement suggests a design that can house electrical and other utilities, potentially hiding wires and cables while allowing easy access when needed.

4. Applications

- Education Buildings: The design's adaptability makes it appropriate for educational settings that require versatile spaces, such as lecture halls, seminar rooms, or study areas.
- Design of Existing Buildings: Due to the lightweight and adaptable nature of the structure, it is applicable to redesign the interior of existing buildings without requiring extensive construction work.

5. Environmental and sustainability considerations

- By minimizing the amount of waste and optimizing resources, lightweight materials and modular components can reduce the environmental footprint of construction.
- Using sustainable and recyclable materials enhances the artifact's value in modern construction if the materials chosen are sustainable and recyclable.

This evaluated artifact includes three main digital processes: digital design and simulation, digital fabrication and kinetic movement.

5.7.1 Digital design and simulation

The figures present detailed digital simulations using Rhino, Grasshopper, and AutoCAD for the design process. To establish and refine the parametric relationships and kinetic behaviors of the wall modules, Grasshopper, a visual programming platform tightly integrated with Rhino, was used. Thus, the design is characteristic of the intended space and functionally adaptable to various spatial requirements. The final details of the design include AutoCAD as the digital tool, and its precision in drafting and ability to translate complex 3D structures into 2D fabrication drawings enabled seamless communication between the digital design phase and physical fabrication (Kolarevic, 2003).

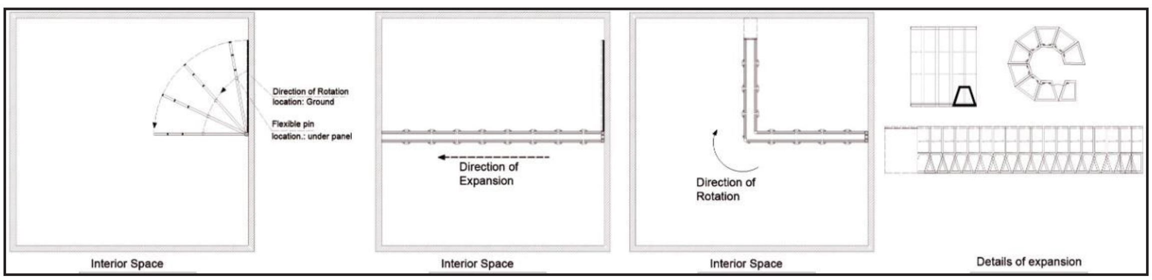

Figure 5.3 Location, Rotation, movement and detail of wall expansion

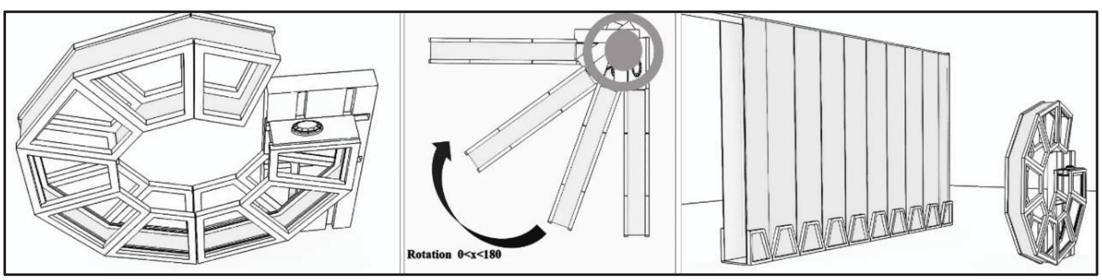

Figure 5.4 Simulation and digital design of dynamic walls through modularity

In addition to being multifunctional in various configurations, movability and modularity, buildings are not static entities but dynamic spaces that can be adapted functionally and aesthetically, aligned with sustainability and adaptability (Scaradozzi et al., 2021).

5.7.1.1 Fabrication Process

Digital fabrication plays a critical role in enhancing the link between digital design and physical construction. In this artifact, a CNC laser cutting machine fabricated the modules following the digital design phase. The selected fabrication method could handle the intricate cuts and patterns in the proposed design. As a result of the small-scale prototype production, some adjustments were done to the assembly methods and the structural integrity of the artifact.

5.7.1.2 Kinetic movement generation

In physical system or structure, kinetic movement generation refers to the process of creating and controlling motion. Movement is produced and managed through the use of mechanical components, actuators, and control systems. In adaptive wall systems, kinetic movement generation enables the wall to change its shape, position, or configuration as a result of specific inputs or environmental conditions. This dynamic capability allows the wall to adapt to various needs, enhancing functionality and user interaction. As a result of actuator movements, a kinetic prototype can evolve and be adapted based on specific architectural requirements and environmental conditions(MARKS, 2016). The kinetic movement of the implemented adaptive wall system is realizable with Arduino microcontrollers. Arduino provides a cost-effective and versatile platform for prototyping the electronic control system that drives wall movements. Using Arduino's programmability, the wall's motion could be adjusted to demonstrate a range of configurations from fully retracted to fully extended, mimicking the full-scale design's conceptual adaptability. The Arduino board is a popular microcontroller board for digital and interactive projects. Arduino is a practical and versatile platform for prototyping the electronic control system that drives the wall's movement. A single magnetic ring enhances signal transmission's clarity, stability, and speed with Arduino's USB Data Sync Cable (ANNEX I).

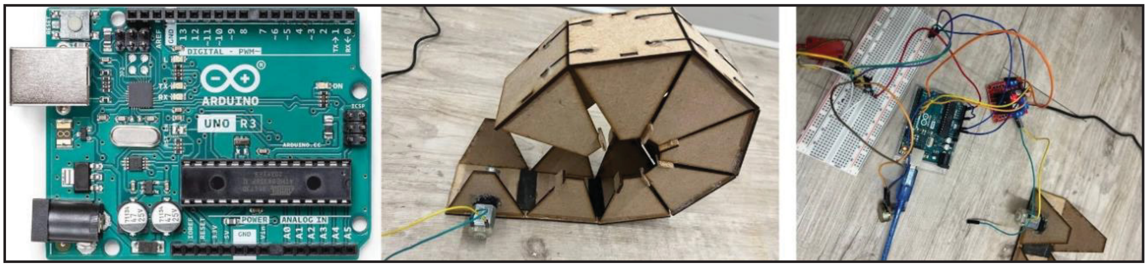

Figure 5.5 Fabrication Process of the artifact based on kinematic features through Arduino

5.7.2 Discussion

Both the literature review and the research emphasize the importance of adaptability in architecture, drawing parallels. In the literature review, it was discussed how modular components can make buildings more sustainable and reusable, allowing them to evolve and transform over time. Specifically, it emphasized the importance of adaptability, which includes both the adaptation of buildings by their users and the modification of buildings in response to changing environments. The proposed framework and the digital mockup created as one of its possible implementations, emphasize the importance of kinetic architecture, which includes mechanical elements that respond to the environment and the needs of the occupants. It also highlights the importance of digital design and fabrication tools, such as parametric design, in creating precise and adaptable spaces. The literature underlines the need for a multidisciplinary approach that integrates digital innovation with sustainable construction practices.

This research presents an exploration of digital design and fabrication processes using tools like Rhino, Grasshopper, and AutoCAD. It focuses on designing an adaptive wall system with intricate geometric details and kinetic behaviors. The research applies principles of modularity and adaptability by designing an adaptive wall system that can reconfigure itself based on spatial needs. Digital tools are used to create detailed 3D models and precise 2D fabrication drawings, translating complex designs into physical structures. The fabrication process employs CAD, CAM, and CNC laser cutting to ensure precision and structural integrity. Kinetic movement is implemented using Arduino microcontrollers, allowing the wall to change its shape and configuration in response to specific inputs or environmental conditions.

This practical application of digital and physical systems demonstrates the concepts discussed in the literature. Both the literature review and the research highlight the benefits of digital design tools and modularity in creating adaptable and sustainable architectural elements. The creation of the prototype implementing the proposed framework, testifies that parametric design and digital fabrication represent a forward-looking approach to construction, emphasizing efficiency and adaptability. As educational buildings benefit from flexible space configurations to support a variety of teaching methods and learning activities, the use of the artifact is particularly appropriate. In addition to its practicality, the structure incorporates utilities within the structure, ensuring that the space remains conducive to its intended use. Modularity and adaptability of the design suggest an easily scalable and modifiable construction system.

The artifact generally represents a harmonious blend of innovation, utility, and sustainability, reflecting a thoughtful response to contemporary architectural and design issues. The framework advances through various stages: from initial input of customer needs to digital modeling, mass customization, and finally digital fabrication. User-centric design incorporates environmental simulation, algorithmic optimization, and interactive animations, allowing for detailed planning and efficient production. While both the proposed framework and the literature explore themes of modularity, adaptability, and sustainability in architecture, the framework focuses more on standardization, digital fabrication, and a structured approach to design and construction; and emphasizes the dynamic and transformative aspects of buildings, drawing on kinetic design principles.

5.8 Evaluation by industry practitioners

The purpose of evaluation of the research is to investigate how implemented artifacts interact with their real-life surroundings. To assess implementation and resolve issues, surveys are particularly valuable, since they provide insight into what is actually going on in the real world (Wieringa, 2014). As a result of this approach, pivotal factors influencing adaptability were suggested, such as usability, durability, and user-centric design. Furthermore, the survey provided an opportunity for participants to express their insights on extra metrics for evaluating adaptability like resilience and environmental control.

5.8.1 Survey and interviews

The industry practitioners' evaluation involved conducting individual interviews with 17 participants, during which the problem, research method, framework, and demonstrations were explained essential. Additionally, the evaluators completed a 17-question survey divided into three sections (ANNEX II). The first section aims to gain insight into the knowledge and perspectives surrounding digital design, digital fabrication, and modularity. The tailoring of buildings to specific needs and preferences is significant, which fosters adaptability, user satisfaction, and long-term functionality. In the second section, the attitude toward technology, its applicability, productivity, and utilization are evaluated. The success of kinematic design in adaptable buildings has two primary factors: ease of use and durability/reliability, which contribute 41.7% to their effectiveness. Though aesthetics and design coherence are essential in overall appeal, they hold a lesser weight at 15.7%. The importance of ensuring intuitive operation and robustness in adaptable building designs cannot be overstated to achieve optimal functionality and user satisfaction.

An evaluation of the methodology, framework, and results of the research is in the final section of the survey. As a result of the responses to the question regarding additional indicators for measuring adaptability in a system or process, various factors were considered essential for assessing adaptability. Several respondents emphasized the importance of adaptability, resilience, and responsiveness to change, whereas others suggested specific elements such as durability, quality, and control of light and heat. Some factors include considerations for adaptability, including the efficiency of resources, user-friendliness, and the ability to transform walls or control light. Several respondents emphasized resilience, modifiability, interoperability, and reconfigurability as critical factors, emphasizing their importance along with movability, scalability, convertibility, and adjustability. Responses emphasize the multifaceted nature of adaptability, encompassing factors such as resilience, efficiency, user-friendliness, and the ability to adapt to changing circumstances. The participants stressed the

importance of customizing buildings to meet specific needs, which enhances their functionality. In addition to ease of use and durability, aesthetic appeal was considered less important for successful design. In addition, respondents emphasized the importance of factors such as resilience and user-friendliness when it comes to achieving adaptability. These insights benefit architects and designers seeking to create flexible and efficient building solutions.
The following questions and answers refer to the 17 questions in the survey and indicate the percentage of responses:

- **Which element of fabrication technology impacts adaptable building design the most?**

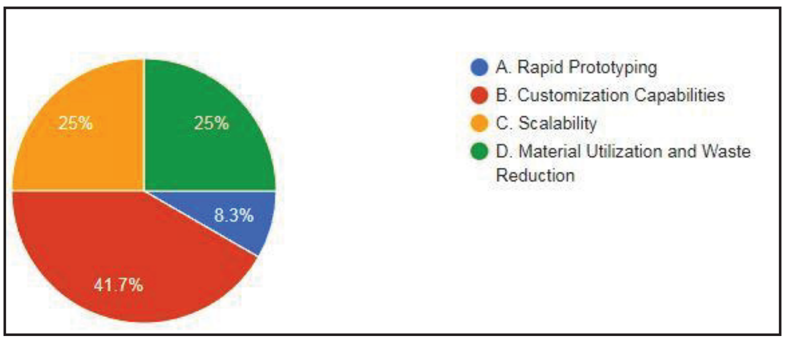

Figure 5.6 Percentages of elements of fabrication

In adaptable building design, each element significantly impacts flexibility:

A. Rapid Prototyping (20%):

- Accelerates design iterations, fostering innovation and responsiveness to change. It allows architects and designers to create physical prototypes of their concepts, facilitating experimentation and iteration. By rapidly testing different ideas and configurations, designers can identify strengths and weaknesses early in the process.

B. Customization Capabilities (35%):

  - Tailor's buildings to specific requirements, promoting user satisfaction and adaptability. Customization capabilities have the most substantial impact, representing 35% of the influence on adaptable building design. Customization enhances functionality and promotes user's satisfaction by allowing spaces to reflect individual preferences and needs.

C. Scalability (25%):
   - Facilitates adjustment to varying demands, enhancing long-term flexibility and resilience. Fabrication technologies that support modular construction, prefabrication, or adaptable components enhance scalability by enabling rapid assembly, disassembly, and reconfiguration.

D. Material Utilization and Waste Reduction (20%):
   - Optimizes sustainability by minimizing waste and maximizing resource efficiency. Fabrication technologies that optimize material utilization and reduce waste are vital in sustainability and cost-effectiveness.
   - Digital fabrication, parametric design, and robotic construction enable precise material cutting, shaping, and assembly, minimizing waste and maximizing structural efficiency.

➢ **Which of the following do you consider most crucial for the success of kinematic designs in adaptable buildings?**

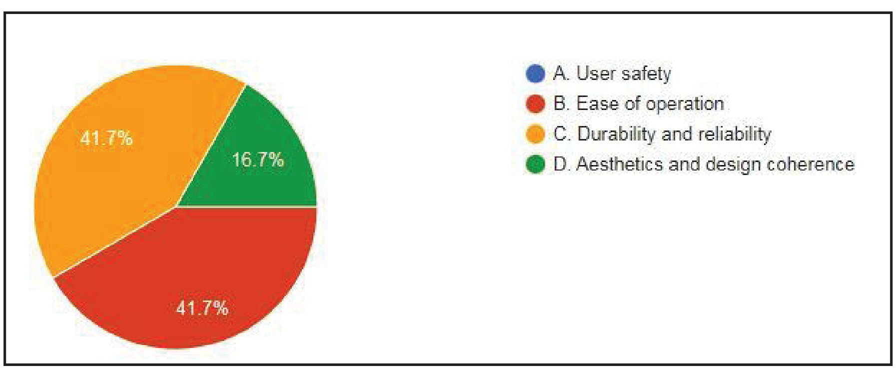

Figure 5.7 Percentages of elements of fabrication

Technology that impact adaptable building design A. User safety (1%): While crucial, it represents only 1% of the factors affecting kinematic designs in adaptable buildings.

B. Ease of operation (41.7%): Crucial for success, it represents 41.7% of factors. Easy operation enhances usability and satisfaction.
C. Durability and reliability (41.7%): Equally crucial, accounting for 41.7%. Ensures that the kinematic elements have long-term functionality and minimal maintenance.
D. Aesthetics and design coherence (15.7%): Important, but less so, at 15.7%. It enhances appeal but ranks lower in importance compared to usability and durability.

5.9 Conclusion

The proposed framework proposes a new strategy for adaptive design in educational environments by bridging the gap between traditional architectural practices and contemporary digital methodologies. Incorporating modularity and kinetic elements makes educational spaces more adaptable and responsive to the changing requirements and user needs and more aesthetically dynamic. Digital fabrication techniques enhance precision and efficiency, contributing to the environmental sustainability of these structures. The research shows strategies for architectural practices to evolve and meet modern demands, particularly in educational settings. This evolution includes adaptability, sustainability, and technological integration. Providing a comprehensive approach that balances aesthetic appeal with practical functionality ensures that educational buildings are ready for future challenges. This paper's findings have the potential to contribute to a more dynamic, responsive, and responsible approach to architectural design in designing educational interior and exterior elements.

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CONCLUSION

In conclusion, this thesis underscores the pivotal role of adaptable building designs in addressing the challenges and needs within the construction industry. This study presents a comprehensive framework grounded in modularity and digital design principles by integrating Design for Manufacture and Assembly (DfMA) principles with digital design and fabrication technologies, employing Design Science Research as the underlying methodology. Through theoretical exploration and practical real-world application, this research demonstrates the significant benefits of modularity, digital design, and fabrication in construction endeavors. Also, there are potential points include minimized material waste, and improved overall project efficiency, leading to a more sustainable future for the industry.

The framework provided guidelines for designing and fabricating modular components, ensuring they are standardized, replaceable, and upgradeable. Specific components and enablers for interior walls of buildings were designed and fabricated, including kinetic wall patterns and kinetic interior elements. These components were designed for functionality, demonstrating the feasibility and effectiveness of modular construction techniques. The framework was implemented, showing significant reductions in construction time and material waste. Feedback was used to refine the framework further, confirming its scalability and potential for larger applications.

Moreover, this thesis emphasizes the alignment of construction practices with circular economy principles, highlighting the importance of sustainability, resource efficiency, and adaptability throughout the building lifecycle. The synthesis of modularity, DfMA, and digital fabrication charts an evolutionary course for the construction sector, promising buildings that respond effectively to changing needs and conditions. The overall aim of this research was to enhance the level of flexibility and adaptability of buildings through modularity, DfMA, digital design, and digital fabrication. The objectives and corresponding results are as follows:

- **Create a framework of modularity, digital design, and fabrication as enablers for adaptable buildings**: A comprehensive framework was developed, integrating guideline for creating adaptable building designs that can easily accommodate changing needs and conditions.

- **Design and fabricate enablers for demountable parts of buildings**: Specific components and enablers for demountable parts were designed. These included modular wall panels, and connectors. Transparency and opacity play crucial roles in the design and functionality of adaptable buildings. These elements influence various aspects of architectural performance, including energy efficiency, aesthetics, privacy, and the adaptability of interior and exterior spaces. Transparent partitions can be used to create flexible interior layouts that can be easily reconfigured without compromising the sense of openness.
- **Partial implementation of the framework on a real-world project**: The framework was partially implemented, showcasing its practical application. This implementation highlighted the benefits of using kinetic patterns and improved project efficiency, reinforcing the framework's validity and potential for broader application. Kinetic elements such as movable walls and partitions allow for the quick reconfiguration of interior spaces. This flexibility is essential in multi-use buildings, where spaces need to be adapted for different functions such as meetings, events, or private work areas. Buildings equipped with kinetic elements can adapt to changing needs over time, extending their functional lifespan and reducing the frequency of major renovations.

Despite the comprehensive nature of this study, certain limitations must be acknowledged. One limitation is the scope of real-world applications, which was limited to specific case studies and controlled environments. Future work could expand this scope by implementing the framework in diverse and more complex projects to validate its versatility and scalability further. Another limitation lies in the variability of construction practices across different regions and the adaptability of the proposed framework to these varying practices. Future research should explore the customization of the framework to accommodate regional construction norms and regulations.

Additionally, while the framework addresses the design and fabrication of modular components, the integration of these components with existing structures was not extensively covered. Future work should focus on developing methodologies for seamlessly integrating modular components with existing buildings and its structure to enhance their adaptability. This thesis makes several significant contributions to the field of construction engineering and management. Practical demonstration, through real-world applications, the study demonstrates the feasibility and effectiveness of modular construction techniques, providing tangible examples of reduced construction timelines and material waste. Aligns construction practices with circular economy principles, promoting sustainability, resource efficiency, and adaptability in building design. By addressing these aspects, the thesis not only advances academic knowledge but also provides practical tools and insights for the construction industry, contributing to its evolution towards more adaptable, efficient, and sustainable practices. By emphasizing the seamless coordination of Digital Design, Digital Fabrication, Modularity, and Design for Manufacture and Assembly, the framework advances the understanding of how these techniques can be effectively combined to enhance the adaptability and functionality of architectural projects. The incorporation of nature-inspired elements into the Conceptual Framework adds a novel dimension to the research, offering innovative solutions that balance opacity and transparency to meet user's needs in various contexts. This approach not only enriches theoretical knowledge but also provides practical applications that can revolutionize how spaces are designed and utilized, particularly in educational buildings. The iterative process emphasized throughout the research ensures continuous validation of concepts, making the findings highly relevant and applicable. Detailed engineering plans, prototypes, and digital mock-ups serve as tangible outputs of the research, bridging the gap between theory and practice. The focus on testing and verifying artifact functionality ensures that the research has direct implications for real-world applications, providing industry professionals with validated methods and tools for optimizing design and construction processes. The contributions lie in advancing interdisciplinary knowledge, promoting innovation in architectural design, and providing practical methodologies that can be implemented in industry to create more adaptable, sustainable, and user-centered spaces.

RECOMENDATIONS

This figure presents a synthesis of a thesis that focuses on developing adaptable building designs through a series of conceptual frameworks. The figure provides an overview of how the thesis develops and applies three distinct but related conceptual frameworks to achieve the goal of creating adaptable buildings. A breakdown of the key components:

Frameworks:

First Framework: Conceptual Framework for Design for Manufacture and Assembly (DfMA) through Modularity & Digital Design (DD): This framework emphasizes the importance of modularity and digital design in achieving efficient manufacturing and assembly processes. It likely focuses on how these techniques can streamline the construction process and enhance the adaptability of building components.

Second Framework: A Conceptual Framework through Digital Design (DD) & Digital Fabrication (DfAB) for Adaptable Elements: This framework builds on the first by integrating digital fabrication techniques. It aims to create adaptable elements within the building design, which can be easily modified or reconfigured based on changing needs.

Third Framework: Proposed Framework for Design for Adaptability: This final framework proposes a comprehensive approach to designing buildings that are inherently adaptable. It likely incorporates lessons from the previous frameworks and focuses on practical implementation strategies.

Central Concept: Adaptable Building: At the center of the slide is the concept of an "Adaptable Building," which represents the ultimate goal of the thesis. The idea is to design buildings that can easily adapt to changing requirements, whether due to user needs, environmental factors, or technological advancements. The results are as the following:

Result 1: Ability to Extract and Transmit Data between Enablers of DfMA and Customer Needs: This result highlights the importance of communication and data exchange between the design/manufacturing processes and the end users' needs. It suggests that the frameworks help in ensuring that the building's adaptability aligns with what the users require.

Result 2: Controlling Opacity & Transparency through Kinetic Patterns: This result focuses on the ability to control the visual and physical properties of the building elements, such as opacity and transparency, using kinetic patterns. This likely refers to dynamic systems that can adjust these properties in response to environmental or user-driven inputs.

Result 3: Utilizing Nature-Inspired Patterns & Kinetics: The final result emphasizes the use of nature-inspired design and kinetic systems to enhance the adaptability of the building. This could involve biomimicry or other design strategies that mimic natural processes to create more responsive and flexible building elements.

These frameworks progressively build on each other, starting with modularity and digital design, incorporating digital fabrication, and culminating in a comprehensive approach to adaptability. The results showcase the practical outcomes of these frameworks, particularly in terms of how data is managed, how building elements can dynamically adapt, and how nature-inspired design contribute to the overall adaptability of the structure.

Figure 7.1 The synthesis of the thesis

The following recommendations can enhance their applications and impacts further:

- Develop strong partnerships with material suppliers to ensure the Framework's environmental goals are feasible and cost-effective.
- Use a Phased Implementation Strategy: When retrofitting and upgrading existing buildings, adopt phased approach to manage costs, minimize disruption, and integrate future technological advances.
- The designers should review and update the framework regularly to incorporate new technological innovations, sustainable materials, and changes in environmental regulations.
- Enhance the user-centric nature of design by engaging the community early in the design process for new constructions and retrofits.
- Promote Smart Technology Integration: Design spaces with smart technologies in mind, enabling future upgrades to building automation systems, energy management, and user interfaces.
- Ensure strict quality control and compliance checks are implemented throughout the design and construction process to meet and maintain the Framework's standards.

With modular design, structures and products can be adapted, expanded, and modified with minimal disruption and cost. In modularity, it is better to incorporate a system that allows components to be easily assembled, disassembled, and reassembled. As part of this system, interchangeable parts can quickly adapt to new functions or improve on existing ones. Ensuring that these modular components include durable materials to withstand multiple assembly cycles is also essential. Consider recyclable or sustainably sourced materials to emphasize the project's eco-friendly aspect. A deeper understanding of the end-user's needs should also be integral to the design process, allowing for personalized configurations that can evolve. A circular economy’s strategy can reduce waste and promote reuse, enhancing the adaptability and sustainability of the product or structure. A graphical expression of the recommendations is given on Figure 7.2 illustrating a comprehensive three-step Strategic Modular Phasing

Framework to optimize building design, fabrication, and assembly using modular components. This approach integrates digital tools throughout construction, enhancing precision and adaptability. The first step is developing digital design, where generative design techniques allow for a broad exploration of possible configurations, ensuring the designs align with client needs and are feasible across various domains. This phase leverages digital modelling tools to visualize and simulate the design, assessing environmental, structural, and performance aspects, and engages all stakeholders to ensure collaborative and informed decision-making. Next, the framework transitions into the preparation and execution of digital fabrication. This preparation involves carefully planning the prefabrication process, ensuring that materials are available, sustainable, and consistent production batch quality. Advanced digital tools check the precision and quality of the modules, ensuring they meet established standards. The coding for machines used in digital fabrication is developed and validated, and then these machines are used to produce the designed components.

The final step is the on-site assembly, which is precise and adaptable to potential uncertainties. It involves efficient logistics to transport prefabricated elements to the construction site and employs robotic tools for precise placement and integration of modules, ensuring the structure meets design specifications and safety standards. The assembled structure is then evaluated by experts for performance, with feedback from this phase integrated into future framework iterations. This framework is not merely a set of procedures but a transformative approach to construction. It signifies a shift towards a more agile, efficient, and sustainable building process, where the adaptability of spaces is front and center. Its emphasis on digital processes and modular components aims to deliver buildings that can evolve with user needs and technological advancements, marking it as a forward-thinking solution in architecture and construction. In contrast to traditional construction methodologies, the SMP Framework advocates a dynamic, integrated approach that emphasizes adaptability and sustainability. It utilizes digital processes and modular components to create buildings that are not only compatible with current technological advancements but can also evolve to meet future user needs. The architecture and construction sector has undergone paradigm shift with this framework. Buildings can adapt more readily to the changing needs of their inhabitants, incorporating efficiency and sustainability in all aspects of their design. Several recommendations can further enhance the effectiveness and impact of the Strategic Modular Phasing (SMP) Framework:

- Develop and use advanced collaborative platforms to facilitate real-time communication and data sharing among all stakeholders. Smoother workflows and integrated decision-making processes would result.
- Standardize modular components and interoperate digital tools used throughout the construction process. By simplifying the integration of different systems and components, the construction process would be more efficient. Integrate comprehensive sustainability metrics into the SMP Framework to evaluate the environmental impact of construction projects.
- Develop scalable prototypes to test modular design and digital fabrication processes in real-world scenarios.
- Utilize AI and machine learning algorithms to optimize design and fabrication processes. These technologies can improve material usage, predict outcomes, and customize design by analyzing vast data.
- Examine the application of the SMP Framework beyond traditional construction projects to include infrastructure, temporary structures, and emergency housing.

The Strategic Modular Phasing Framework can significantly advance the fields of architecture and construction by implementing these recommendations, resulting in more efficient, adaptable, and sustainable building practices. The Strategic Modular Phasing Framework (SMP) introduces a transformative approach to architecture and construction using digital and modular techniques to enhance efficiency, adaptability, and sustainability. To fully utilize its potential, it is necessary to take into account several inherent limitations:

- Digital Accessibility and Cost: High upfront costs and accessibility issues can pose significant barriers, particularly for smaller businesses or projects.
- It relies on seamless coordination among diverse stakeholders and integrating complex systems, increasing the risk of errors and miscommunication.

- Building codes and standards may not fully accommodate the framework's innovative approaches, potentially hindering its adoption.
- Even with a focus on sustainability, the production and transportation of modular components and material selection are essential.
- Fast technological change risks quickly rendering current digital tools and fabrication equipment obsolete, requiring ongoing investments.

Taking on these challenges requires a collective effort from industry stakeholders. As a result, the SMP Framework can help drive forward more resilient and sustainable construction industry.

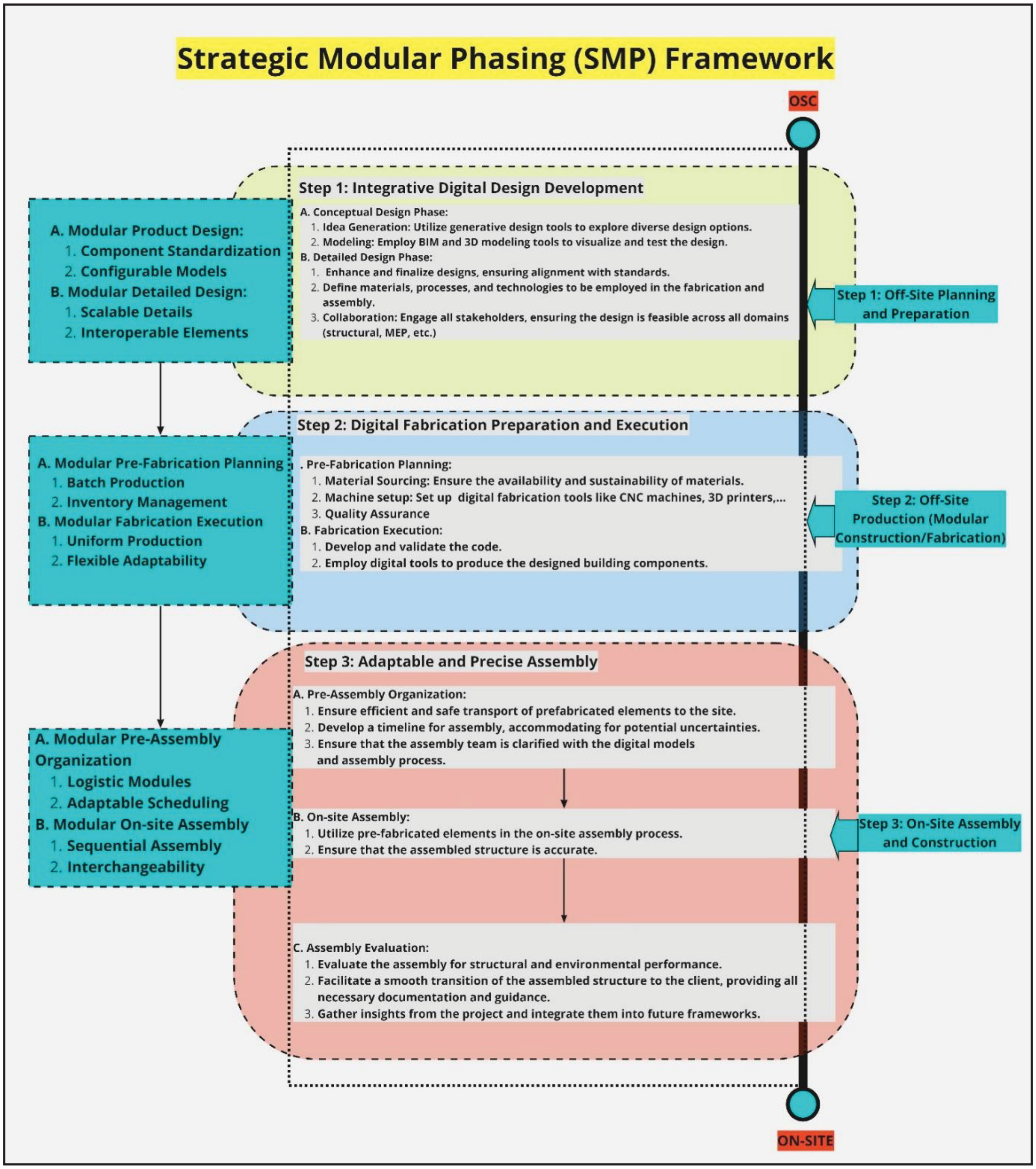

Figure 7.2 The strategic modular phasing (SMP) framework

ANNEX I

CHAPTER 5 - DESS - KINEMATIC ARTIFACT SPECIFICATIONS

The following figures illustrate the information and details of Mock-up in the thesis.

1. USB Data Sync Cable for Arduino UNO R3 Board ATMEGA328P MEGA2560 about 1.5M / 4.9FT Long

Table A I-1 USB Data Sync Cable for Arduino's specification

Brand	naughtystarts
Connector Type	USB Type A
Cable Type	USB
Compatible Devices	Monitor, Server
Special Feature	Magnetic

• Type: USB 2.0 Type A Male to Type B Male Connection Cable.
• Cable Length: about 1.5M / 4.9FT Long. Color: Transparent Blue.
• A single magnetic ring makes the signal transmission clear, stable and fast.
• USB Data Sync Cable for Arduino UNO R3 Board, ATMEGA328P and MEGA2560 Modules.
• Compatible with USB B ports of printer, scanner, fax, server, monitor, hard disk, and keyboard.

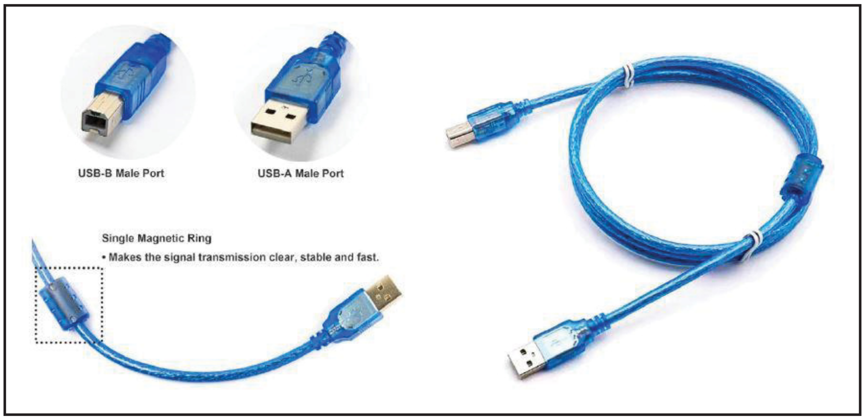

Figure A I-1 USB Data Sync Cable for Arduino's specifications

2. MTDZKJG 12V 2A Power Supply AC Adapter 100-240V AC to DC Adapter Plug 5.5 x 2.5mm & 2.1mm 12Volt 24W 2000mA 1500mA 1000mA Power Converter for CCTV Router Speaker Webcam DC 12V Transformer

Table A I-2 Power Supply AC Adapter's specifications

Color	black
Input Voltage	120 Volts
Amperage	1 Amps
Brand	MTDZKJG
Connectivity Technology	DC Tip
Connector Type	Barrel Connector
Included Components	power adapter, DC connector

1. Input: AC 100V-240V 50/60Hz; Output: DC 12V, 2A 24W MAX; DC plug size is 5.5mm x 2.5mm. Compatible with 5.5mmx2.1mm. Polarity is inside positive "+", outside negative"-", Power cord length: about3ft.

• 2. 12Volt 2A 1.5A 1.0A 0.8A 0.5A Switching Power Supply, DC 24W Max, Power supply works for several devices which require a less than 12.0V 2A 24W power adaptor, Such as 12V 2000mA, 1500mA …

Figure A I-2 Power Supply AC Adapter

3. L298N Motor Drive Controller Board Module Dual H Bridge DC Stepper for Arduino Smart Car Robot R3 2560 ESP32 ESP826

Table A I-3 Motor Drive Controller's specifications

Brand	DIYmall
Special Feature	Low light
Human Interface Input	Buttons
Item Dimensions LxWxH	1.6 x 1.6 x 0.8 inches
Item Weight	0.02 Pounds
Graphics Card Description	Dedicated
Cooling Method	heat

• L298N as main chip, low heat, outstanding anti-interference performance

• High working power to 46v, large current can reach 3A MAX and continue current is 2A, power to 25w

• Can drive one 2-phase stepper motor, one 4-phase stepper motor or two DC motors

• Large capacity filter capacitance, more stable and reliable

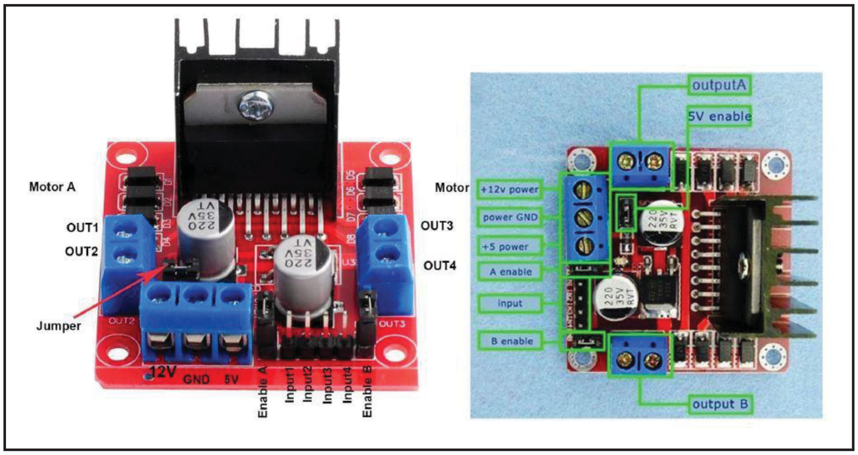

Figure A I-3 Motor Drive Controller

4. BB830 Solderless Plug-in Breadboard, 830 tie-points, 4 Power Rails, 6.5 x 2.2 x 0.3in (165 x 55 x 9mm)

• 830 tie points totals: 630 tie-point IC-circuit area plus two 100 tie-point distribution strips providing 4 power rails.

• White ABS plastic body with black printed legend. Colour legend on distribution strips.

• Contacts are Phosphor Bronze with Plated Nickel Finish, rated for 50,000 insertions. Rated at 36 Volts, 2 Amps.

• Insertion Wire Size is 21 to 26 AWG, 0.016 to 0.028 inches diameter (0.4 to 0.7mm diameter)

• Size: 6.5 x 2.2 x 0.3in (165.1 x 54.6 x 8.5mm). Peelable adhesive tape backing is provided for attaching to a surface.

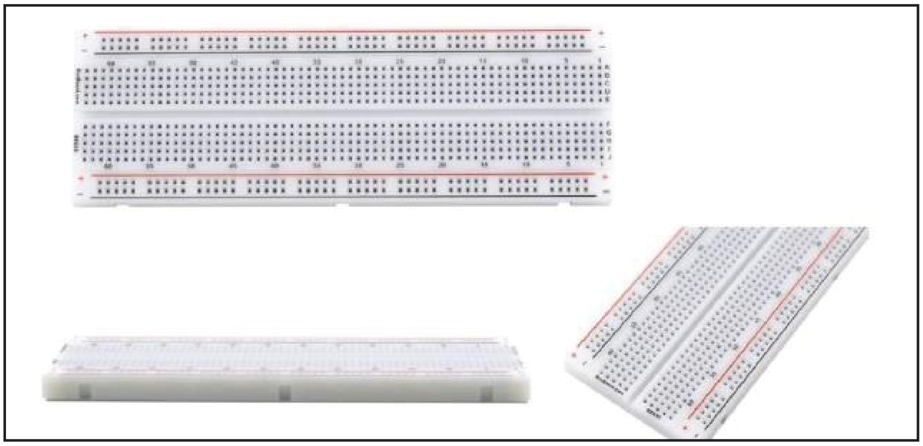

Figure A I-4 Solderless Plug-in Breadboard

1. Arduino Uno REV3 [A000066]

Table A I-4 Arduino's specifications

Brand	Arduino
Model Name	Rev 3
Ram Memory Installed Size	32 KB
Memory Storage Capacity	32 KB
Connectivity Technology	USB

• This board is the entry to the unique Arduino experience: great for learning the basics of how sensors and actuators work and an essential tool for the rapid prototyping needs
• Arduino Uno is the most used and documented board in the world
• "Uno" means one in Italian and was chosen to mark the release of Arduino Software (IDE) 1.0, now evolved to newer releases
• It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button
• Arduino is an open-source hardware, software, and content platform with a worldwide community of over 30 million active users.

Figure A I-5 Arduino Uno REV3

ANNEX II

CHAPTER 5 - DESS - EVALUATION QUESTIONNAIRE

Table A II-1 The 22 survey questions provided to the evaluators

N	Introduction This section covers the evaluator’s background information:
01	Name and Email address?
02	What is your professional role in the building design and construction industry or academic fields?
03	How many years of experience do you have in this field?
04	On a scale of 1 to 4, how familiar are you with the concept of modularity in design and construction? (1 = Not Familiar, 4= Very Familiar)
05	Have you used digital design tools (e.g. CAD software) in your architectural or construction projects? (Yes/No)
06	How familiar are you with the concepts of CNC, robotics, and digital fabrication in building design and construction?
N	Attitude towards Technology
07	How do you perceive the role of CNC and robotic technology in enhancing digital fabrication processes?
08	How important do you think is the role of modularity in modern building design and construction?
09	How do you envision the future of adaptable design, considering modularity, digital design, and DFMA principles? (Open-ended)
010	Have you encountered any challenges in implementing digital fabrication technologies in your projects?

N	Use of Digital design methods and techniques (parametric design, etc.)
011	Which of the following do you consider most crucial for the success of kinematic designs in adaptable buildings? A. User safety B. Ease of operation C. Durability and reliability D. Aesthetics and design coherence
012	In the context of digital design, which of the following do you deem most significant? A. User Interaction and Experience B. Visualization and Prototyping C. Coordination and Collaboration D. Information Management
013	Which aspect of DFMA do you find most valuable for adaptable buildings? A. Efficient manufacturing processes B. Ease of assembly/disassembly C. Reduced waste D. Improved quality control
014	What do you perceive as the primary advantage of modular designs? A. Flexibility and adaptability B. Cost-effectiveness C. Rapid assembly and disassembly D. Sustainability
015	How do you perceive the future role of digital fabrication in modular building?

016	What is your stance on the sustainability aspects of implementing digital fabrication in building projects?
N	Visual Feedback (diagrams/photos)- Recommendations
017	How clearly do the provided diagrams and photos illustrate the concept of modularity in design and construction? (Rate on a scale of 1 to 4, 1 being 'Not Clear at all' and 4 being 'Extremely Clear')
018	Do the visuals effectively demonstrate the transition from digital design to on-site operation? (Yes/No). If possible, please make a brief explanation.
019	How do you evaluate the adaptability and functionality of the design depicted in the image/diagram?
020	What do you see as the primary barriers to the adoption of digital fabrication technologies in building design and construction?
021	What kind of challenges do you anticipate in scaling up the use of CNC and robotics across diverse projects?
022	Please provide any additional comments or insights that you think would be valuable for this research.

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