CONFORMING TO FUTURE CHANGES IN BUILDINGS: A COMPONENT-ORIENTED DETAILING STRATEGY

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ABSTRACT

CONFORMING TO FUTURE CHANGES IN BUILDINGS: A COMPONENT-ORIENTED DETAILING STRATEGY

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The conventional approach to building design typically involves rigid structures with interdependent relations between building materials, components, systems, and spatial elements. However, buildings should be able to adapt and transform over time to accommodate various needs such as maintenance, repairs, functional changes, aesthetical enhancements, and technological improvements. Recognizing the drawbacks of the non-adaptable building structures in current practices, this study proposes a component-oriented decision-making strategy to extend the useful life of buildings and foster a more adaptable and sustainable built environment. The proposed strategy investigates the necessary feedback mechanisms throughout the building`s lifecycle, from the early design phase to the use phase, aiming to ensure continuous changeability in building components. In order to assess how such a strategy could facilitate the management of the building's beneficial life cycle with control over the components, an architectural detailing example, and a case study were examined. The framework suggested in this study aims to enhance the adaptability of buildings by assisting architects in the design phase with alternative selections at the component scale. To that end, an architectural detail was evaluated in the early design phase by developing the system architecture model. Design

Structure Matrix was employed to breakdown building structure and analyze the relationships between building components. This analysis was supplemented with information including geometric evaluations of components, connections, assembly sequences, and service life compatibility of components. The working mechanism of the designated feedback system was visualized with an anticipated interface for digital design tools. For the use phase, the aim of the suggested strategy is to improve building operations by informing occupants about the building structure's transformability and recommending efficient timing for maintenance and changes. The operational flow of the feedback mechanism was presented for an educational setting, using a digital twin of the building coupled with necessary data sets and sensor networking. Overall, this strategy not only develops the initial considerations of architectural detailing in the early design process but also improves change management in building components during the use phase, thereby contributing to a more adaptable and sustainable built environment.

Keywords: Detailing Strategy, Feedback Mechanism, Building Adaptability, Design Structure Matrix, Digital Twin

ÖZ

BİNALARDA GELECEKTEKİ DEĞİŞİKLİKLERE UYUM SAĞLAMA: BİLEŞEN ODAKLI BİR DETAYLANDIRMA STRATEJİSİ

Çankaya Topak, Sıla
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Bina tasarımına yönelik geleneksel yaklaşım tipik olarak yapı malzemeleri, bileşenleri, sistemleri ve mekânsal elemanları arasında birbirine bağlı ilişkilere sahip katı yapıları içerir. Ancak binaların bakım, onarım, işlevsel değişiklikler, estetik iyileştirmeler ve teknolojik gelişmeler gibi çeşitli ihtiyaçları karşılayacak şekilde zaman içinde uyum sağlayabilmesi ve dönüşebilmesi gerekir. Mevcut uygulamalardaki uyarlanamayan bina yapılarının dezavantajlarının farkında olan bu çalışma, binaların kullanım ömrünü uzatmak ve daha uyumlu ve sürdürülebilir bir yapılı çevreyi teşvik etmek için bileşen odaklı bir karar verme stratejisi önermektedir. Önerilen strateji, erken tasarım aşamasından kullanım aşamasına kadar binanın yaşam döngüsü boyunca gerekli geri bildirim mekanizmalarını araştırarak bina bileşenlerinde sürekli değişkenlik sağlamayı amaçlamaktadır. Böyle bir stratejinin, bileşenlerin kontrolü ile binanın faydalı yaşam döngüsünün yönetimini nasıl kolaylaştırabileceğini değerlendirmek için bir mimari detaylandırma örneği ve bir vaka çalışması incelenmiştir. Bu çalışmada önerilen çerçeve, bileşen ölçeğinde alternatif seçimlerle mimarlara tasarım aşamasında yardımcı olarak binaların uyarlanabilirliğini arttırmayı amaçlamaktadır. Bu amaçla erken tasarım aşamasında sistem mimarisi modeli geliştirilerek mimari bir detay değerlendirildi. Bina yapısını parçalamak ve bina bileşenleri arasındaki ilişkileri analiz etmek için Tasarım Yapısı Matrisi kullanıldı. Bu analiz; bileşenlerin geometrik değerlendirmeleri, bağlantılar, montaj sıraları ve bileşenlerin hizmet ömrü uyumluluğu gibi bilgilerle desteklendi. Belirlenen geri bildirim sisteminin çalışma mekanizması, dijital tasarım araçları için beklenen arayüz ile görselleştirildi. Kullanım aşaması için önerilen stratejinin amacı, bina sakinlerini bina yapısının dönüştürülebilirliği hakkında bilgilendirerek ve bakım ve değişiklikler için verimli zamanlama önererek bina operasyonlarını iyileştirmektir. Geri bildirim mekanizmasının operasyonel akışı, binanın dijital ikizi ve gerekli veri setleri ve sensör ağı kullanılarak bir eğitim ortamı için sunuldu. Genel olarak bu strateji, yalnızca erken tasarım sürecindeki mimari detaylandırmanın ilk değerlendirmelerini geliştirmekle kalmaz, aynı zamanda kullanım aşamasında bina bileşenlerindeki değişim yönetimini de geliştirir, böylece daha uyumlu ve sürdürülebilir bir yapılı çevreye katkıda bulunur.

Anahtar Kelimeler: Detaylandırma Stratejisi, Geri Bildirim Mekanizması, Bina Uyarlanabilirliği, Tasarım Yapısı Matrisi, Dijital İkiz

To

my beloved husband Fatih

my little sunshine Ela

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
2D	Two Dimensional
3D	Three Dimensional
4D	Fourth Dimension
5D	Fifth Dimension
AEC	Architecture Engineering Construction
BEES v4.0	Building for Environmental and Economic Sustainability
BIM	Building Information Modeling
BOL	Beginning of Life
BSI	Building Systems Integration
CAD	Computer-Aided Design
CDW	Construction and Demolition Waste
CE	Circular Economy
CHS	Century Housing System
CIB	International Council for Building
CO_2	Carbon Dioxide
DfC	Design for Changeability
DSM	Design Structure Matrix
DT	Digital Twin
DTs	Digital Twin Application Subsystem
EN	European Standards
EOL	End of Life
EPDs	Environmental Product Declarations
GPS	Global Positioning System
HVAC	Heating Ventilation and Air Conditioning
ID	Identification
IFC	Industry Foundation Classes
IoT	Internet of Things
IR	Infrared Radiation

ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
ML	Machine Learning
MOL	Middle of Life
NASA	National Aeronautics and Space Administration
PM	Particulate Matter
RF	Random Forest
RFID	Radio Frequency Identification
SI	Support and Infill
SVM	Support Vector Machine
US Air Force	United States Air Force
US Census Bureau	United States Census Bureau
UWB	Ultra-Wideband
VMP	Virtual Environment Platform
VOC	Volatile Organic Compounds
WIFI	Wireless Fidelity
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

> “Buildings aren’t made out of glass, concrete, and stone:
> they’re made out of time, layers of time.”
> *(Frank Duffy)*

As a major contributor to socio-economic development, the building sector uses primary energy and natural resources. Buildings are responsible for 40% of energy consumption (UNEP SBCI, 2009), and around 30% of resources used (Benachio, Freitas, & Tavares, 2020). The research by the World Resource Institute conducted in a number of industrialized countries outlined that one-half to three-quarters of the annual material input was left to the environment as waste every year (Matthews et al., 2000; Osmani & Villoria-Sáez, 2019). Excessive energy consumption, depletion of natural resources, and waste generation may be correlated with different life cycle phases of the building from the early design phase to demolition. The issues throughout the building life cycle can be exemplified as inadequate design understanding, unplanned construction practices, or improper operational decisions.

To overcome such problems, the current construction and design practices should be reassessed with emerging concerns and reconsidered in comparison with the developments in other industries. The transition from a linear economy to a circular economy has recently gained increasing interest among various disciplines. In the building sector, this transition has been addressed with adaptability, which has been acknowledged as one of the most effective strategies because buildings are never in an end state but part of a process. Making buildings adaptable and reusable has been considered vital (Galle, 2017).

The conventional practices in the built sector are quite inefficient (Durmisevic, 2006), as buildings are usually designed and constructed as rigid and fixed structures and do not allow for future transformations (Askar, Bragança, & Gervásio, 2021). Most buildings are subjected to being broken down for change, adaptation, upgradation, and replacement if a transformation is desired, which results in waste production, material consumption, and energy loss (Durmisevic, 2006). Buildings should respond to the inevitable changes in user needs over the building lifecycle and should be adaptable to accommodate necessary adjustments.

The adaptable building understanding is in line with the sustainable development goals, enhancing the quality of life for people with healthy environments and improving social, economic, and environmental conditions for present and future generations (Ortiz, Castells, & Sonnemann, 2009). The link between sustainable development and the construction industry is highly significant because the latter has the highest economic priority with significant environmental and social consequences (Burgan & Sansom, 2006). To support sustainable development in the construction industry and to provide the best performance during the operational phase, possible future transformation needs in building components such as maintenance, repair, restoration, renovation, functional modifications, aesthetical changes, and technological improvements should be considered throughout the design process, which will minimize waste generation and energy loss. Adaptability strategies that would extend the longevity of the building/product by accommodating changing circumstances depend highly on the initial decisions for the building systems, building components, and their relations in the design phase.

The role of the architect is generally downsized into an idea of use and place, but architects in this ever-changing era should have access to all the building-related information such as the assembly, products, and materials (Kieran & Timberlake, 2004). Moreover, in the context of an interest in building adaptability, concurring with the transition towards the circular economy, new requirements result in changing demands for architectural designers. The role of the architect will be crucial in the implementation and transition towards a change-oriented construction sector considering both the ability for the depiction of future values and needs, and the skill for discussion and negotiation (Galle, Herthogs, Vandervaeren, & Waldogallevubbe, 2018). Building performance tools have been developed to help the architects control various parameters in the design process. Although the advancements in building performance tools are quite promising, these tools typically aim to evaluate the design rather than to guide it (Attia, Gratia, De Herde, & Hensen, 2012). Guidance for decision-making is very important, especially in early design phases, which include high variability for many design parameters that together create a vast design space (Østergård, Jensen, & Maagaard, 2017). With building information modeling (BIM) technology, integration of the informational texture of designed objects, including material properties, lifecycle settings, and functional usage, became possible for architects and engineers (Ghaffarianhoseini et al., 2017). However, there is limited research for decision-making guidance in the design process regarding the adaptability to accommodate change for the longevity of the building.

1.1 Problem Definition

This study proposes a component-oriented decision-making strategy to prolong the useful life of buildings and to create a more adaptable and sustainable built environment. Conventional building understanding presents building structures with dependent relations between building materials, components, systems, and space. The pattern of making such structures starts with the fixed integration of materials into closed structural systems and results in fixed spatial systems (Durmisevic & Brouwer (2002b) as cited in Durmisevic & Brouwer (2002a)). In these closed systems, building materials and components have different life spans and durability, and they will later have requirements such as maintenance, repair, and change at different life stages. Breaking the wall to repair electrical installation, demolishing the ceramic of the bathroom to change the sanitary equipment or to transform the space for the elderly usage can be listed as some of the examples for such fixed arrangements.

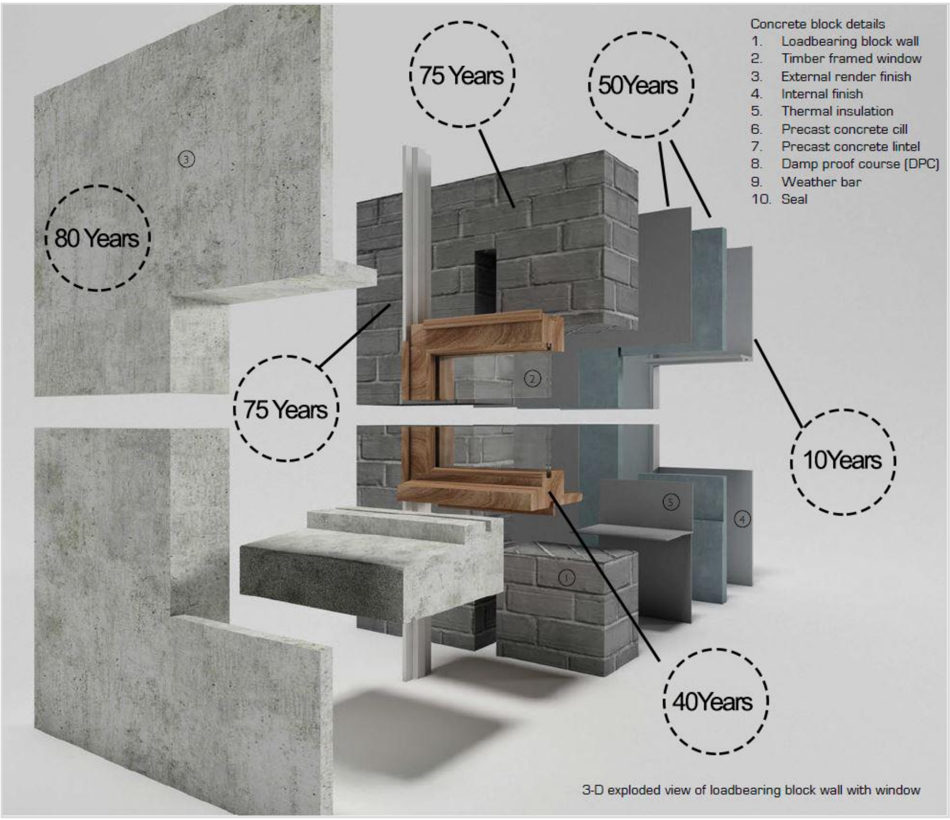


Figure 1.1. Exploded representation of the system with service life and assembly sequences (Image adapted from Watts (2014))

Figure 1.1 explains a building system detail that includes materials with different life spans and assembly sequences. Service life information of the materials demonstrates the approximate service life for the selected materials rather than the exact number. In this system, when there is a need for a change in case of repair or replacement in the timber framed window, the loadbearing block wall will be demolished although it has more than 25-year remaining service life. Therefore, this research is intended to be a useful baseline for developing a decision-making strategy that manages the detail selection process regarding the service life and change requirements in the early design process. This approach not only provides control on detailing selection in the early design process but also proposes an integration method with cutting-edge technologies for the use phase of the building.

1.2 Scope and Objectives

This study aims to develop a detailing strategy with the integration of cutting-edge technologies throughout the building life cycle. To achieve this aim, the study proposes a component-oriented decision-making system to control the system architecture of the building in the early design phase that will be used to accommodate change without damaging the building and creating construction waste.

The main objectives of this research are defined as:

- Developing a decision-making support detailing strategy to guide the architects in the design phase, that will analyze the selected detail terms of connection and service life relations.
- Generating the use-phase framework for the feedback mechanism support to guide the building users in case of change requirements for effective operation throughout the building life cycle.

Accordingly, within the scope of this research:

- The product architecture of the buildings is explored and mapped in terms of connection relations and service life information.
- Service life information of the materials is reviewed and discussed.
- Design Structure Matrix is used to analyze the product architecture of the details and to present the connection and service life relations.
- The components and the requirements for the assembly library are identified and outlined.
- A dataset for the service life information of the materials is formed to predict the material service life with a random forest algorithm.

- Frameworks of feedback mechanisms for the design and use phase are developed and discussed.
- The developed strategy is visualized in a selected case and an interface for the design phase is proposed.
- The use-phase scenario is studied and presented based on the developed framework.

1.3 Research Questions

Within this framework, the main research question corresponding to the main objectives explained is: How can we support architects to control the component relations in the early design phase for effective operation and maintenance in the use phase of the building life cycle?

To answer the main question, sub-questions are formed as follows:

- What are the main problems in the conventional design process, that result in excessive energy usage and construction waste?
- What is the functioning mechanism of the building system? How can we decompose a building to understand the component relations? Which factors are important in evaluating the architectural details?
- How does the feedback mechanism work with the data sets? How can data sets be developed thinking the service life information and connections?
- Which program will be used while guiding the architects? What interface is applicable within the feedback mechanism?
- How does the feedback mechanism work in the use phase? What are the related components to construct real-time data transfer?

1.4 Methodology

This study employs constructive research methodology (constructivist knowledge production). This construction, which depends on the existing knowledge used in novel ways, "proceeds through design thinking that makes projection into the future envisaged solution (theory, artifact) and fills conceptual and other knowledge gaps by purposefully tailored building blocks to support the whole construction" (Crnkovic, 2010, pp.360). Constructive design science research analyzes the usage and the performance of designed artifacts to understand, describe, and develop the designed systems (Crnkovic, 2010). As constructive design science research is mostly utilized in the fields of engineering, computer science, and information systems, their artifacts are systems, applications, methods, data models, data visualizations (Muntean, Danaiata, & Hurbean, 2022), and constructs, models, theories, instantiations, algorithms, human-computer interfaces, system design methodologies and languages (Vaishnavi & Kuechler, 2004).

The study of Hevner, March, Park, & Ram (2004) introduces design-science (constructivist) research guidelines as follows:

i. Design as an artifact: output of the research as a construct, a model, or a method.
ii. Problem relevance: the aim of the study to develop solutions for the related problems in the field.
iii. Design evaluation: the assessment of the artifact in terms of utility, quality, and efficacy.
iv. Research contributions: clear and verifiable contributions of the research with the proposed artifact.
v. Research rigor: the application of methods in the evaluation and establishment of the research.
vi. Design as a search process: the available means to achieve the desired results.
vii. Communication of research: reaching out to both technology-oriented and management-oriented audiences.

This study is developed within the building science field which is an interdisciplinary research area between architecture and engineering. It follows the constructivist research methodology with respect to the aforementioned guidelines. According to that, the research methodology is expressed diagrammatically as follows (Figure 1.2):

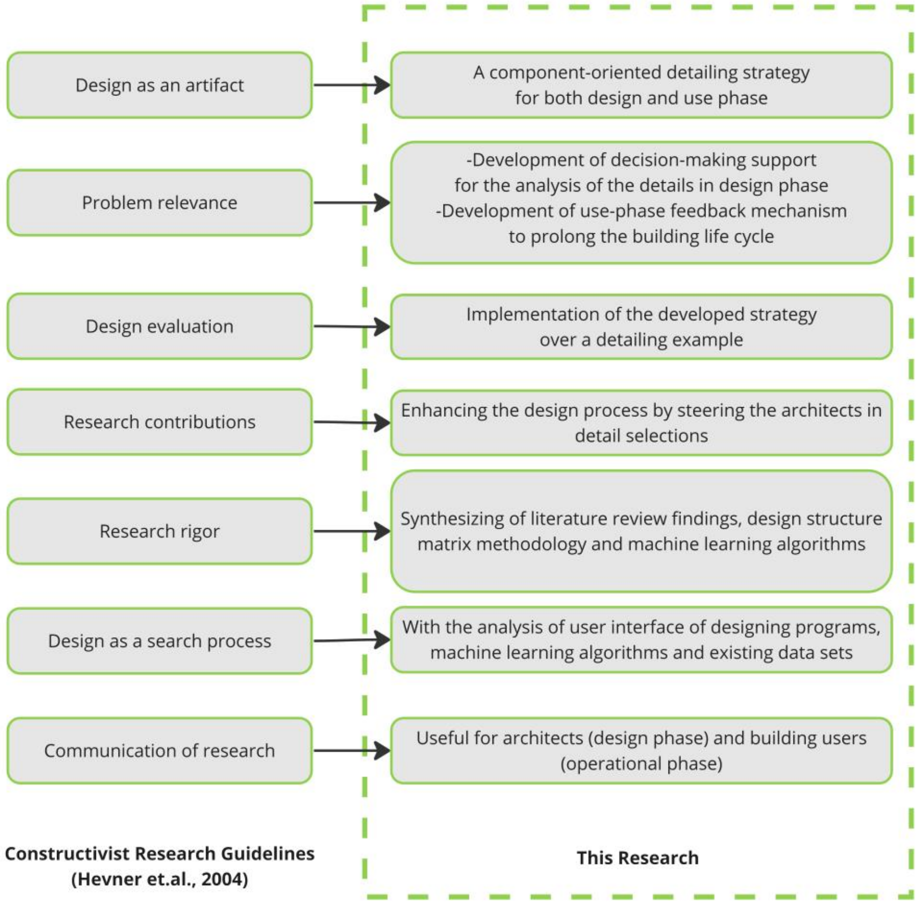


Figure 1.2. Constructive research guidelines and research methodology

1.5 Significance and Contributions

This research aims to develop a decision-making support system for the design process to increase the building adaptability. The feedback mechanisms will enhance the design process by steering the architects with the service life and connection information, that improve the detail relations. Controlling the detail relations in the early phase of the design process will result in beneficial life cycle planning for a building. Unlike the existing literature that predominantly focuses on energy calculations during later design phases, this research seeks to guide architects to consider the future requirements of building components. With this redefinition of the architect`s role, they can contemplate not only about the present version of the design but also about possible future alterations. Moreover, this feedback mechanism will extend into the operational phase of the building to control the building component needs such as maintenance, or repair. Increasing the building adaptability level is crucial in addressing the left-over spaces (in case of functional changes, user changes), technological developments, unforeseen future needs, and more. It will contribute to sustainable development minimizing construction and energy waste.

1.6 Research Structure

Before delving into the chapters of the dissertation, a general overview is presented with the diagram in Figure 1.3. The aim is here to outline the key elements of the research, methodological framework, and research directions, offering a visual roadmap to the content demonstrated in the following chapters. Each section of the diagram refers to a chapter of the dissertation and shows the significant steps in the development of the study.

According to that, it starts with the problem definition of the research. Buildings consist of multiple elements with diverse service lives and are constructed as rigid structures, leading to several issues, particularly during the use phase. Addressing these issues requires an in-depth evaluation of the architectural design process and the role of architectural detailing. Key challenges identified indicate the ambiguity in the design process, uncertainty in boundary definition, the lack of understanding in detailing design, and the lack of circular design understanding.

To tackle these problems, the building design process was reevaluated. The study explores the roadmaps of whole-to-parts decomposition, outlining approaches at both systems and component levels. As the systems-level decomposition offers a broad overview, component-level decomposition provides the meticulous considerations related to the architectural detailing such as the geometry of component edges, life cycle coordination, assembly sequences, and connections.

A literature review of the decomposition approaches was investigated to compile various researchers` aims and methods and synthesize this information to define the methodology for the evaluation of relationships and dependencies of the components and develop the component-oriented detailing strategy. The following section presents the suggested model for the decomposition of building structures to control material dependencies during different phases of design and use. The proposed strategy allows for control over component relationships during the design phase and enables adaptability and transformation through digital design tools during the use phase. The suggested strategy is presented with the examination of an architectural detailing example and a case study as outlined in the following diagram.

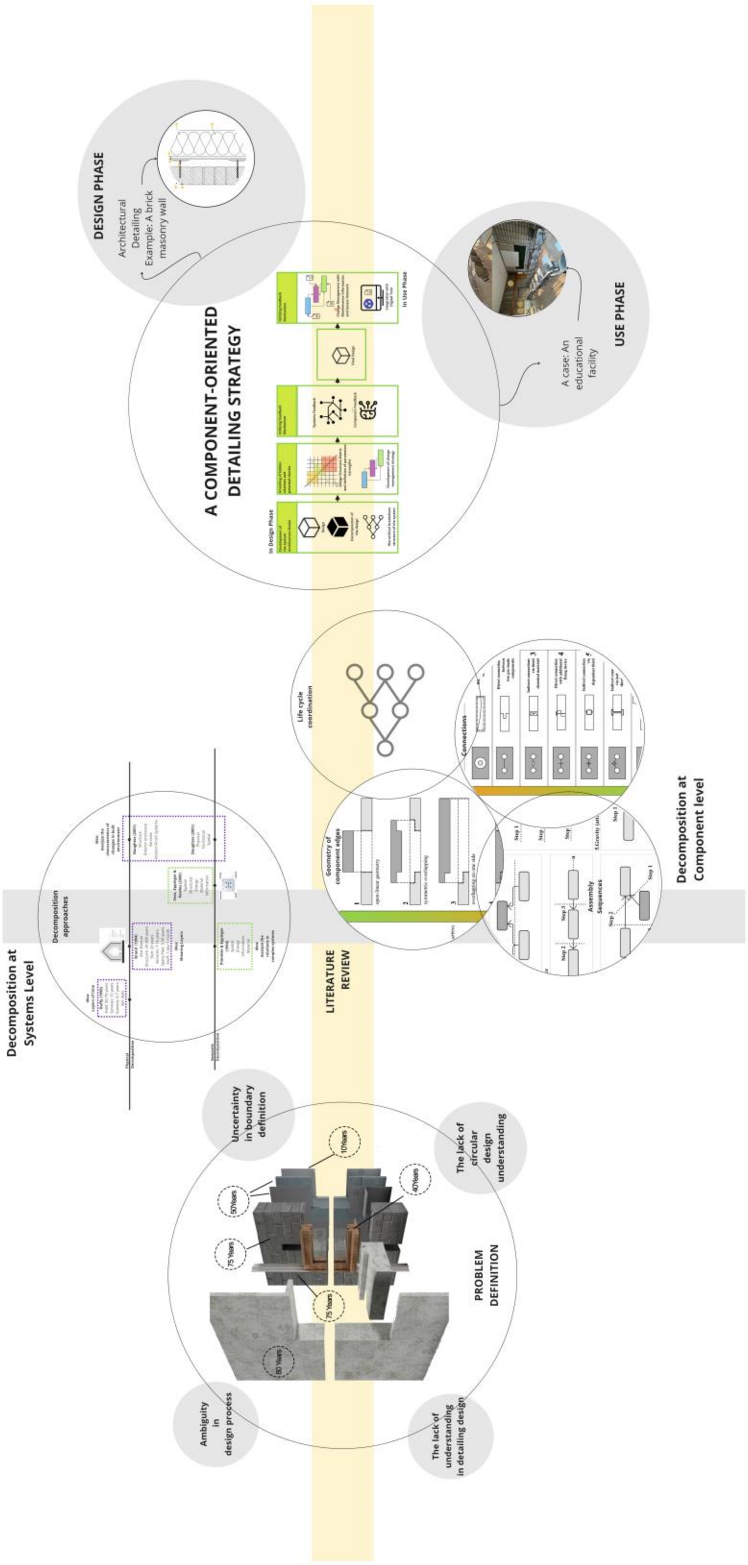


Figure 1.3. Outline of the research

1.7 Disposition

The thesis consists of an introductory chapter, three main chapters corresponding to the research questions, and a concluding chapter, which is demonstrated in Figure 1.4. Following the introductory chapter, Chapter 2 presents the in-depth domain analysis focusing on the several processes in architectural design. It later discusses the common processes in cross-industries to learn them. The chapter concludes by addressing the problems in the building process to indicate the possible research gaps. Chapter 3 composes the theoretical base for the suggested model, providing the decomposition analysis of building structure at multiple levels, spanning from systems to components. It explains the related research methods and the reflection of the decomposition approach to the different digital tools. Based on the literature findings in Chapter 3, Chapter 4 develops the architectural detailing strategy model and implements the model in an architectural detailing example and a case study. Chapter 5 presents the concluding remarks, revisits the research questions, and discusses the limitations. It concludes with the recommendations for future research.

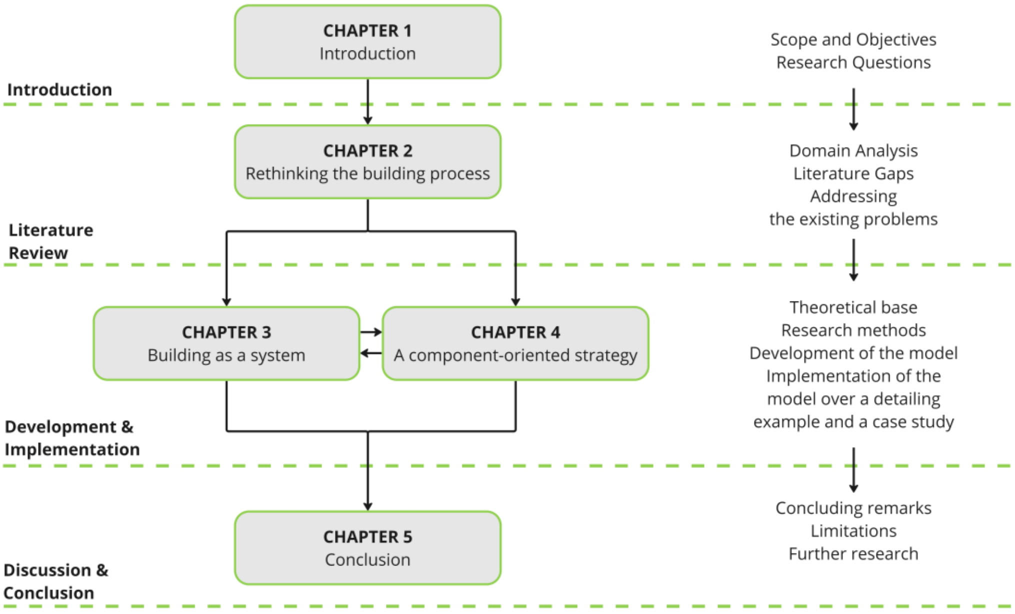


Figure 1.4. Research structure of the study

CHAPTER 2

RETHINKING THE BUILDING PROCESS

> “A building is not something you finish.
> A building is something you start.”
> *(Stewart Brand)*

The built environment includes man-made structures that provide spaces where we live, such as buildings, streets, open spaces, and so on. As the major actor of the built environment, a building can be described as “a complex system where many of its constituent elements or subsystems can be characterized as systems in their own right” (Vibæk, 2014, p.76). The building system composes the physical interrelations with its environment from macro-to-micro scales, such as material relation systems, heating systems, structural systems, and supra-systems including streets, blocks, and cities. This `levelled complexity` (Vibæk, 2014) requires the processes, regulations, and standards to be controlled and managed. To advance the operational process in construction, it is essential to understand the design process and detect the problems by examining the present conditions in the field and to seek solutions by analyzing the cross-industry. This chapter delves into the design process in construction with a focus on detailing understanding of construction, elaborates on the emerging subjects, and discusses similar systems in the manufacturing sector to reveal related implications.

2.1 Architectural design process

The development of an architectural project is a long-term design process from its beginning through to completion. Design includes four distinct phases: Discover, Define, Develop, and Deliver. It begins with comprehensive research and thinking, is narrowed down, focuses on design aims, and finally composes a solution for the problem (Design Council, 2003). The phases of design are ramified in terms of the class of design problem (ex. architectural design problem, product design problem) and develop their own phases. According to the study of El Khouli, John, & Zeumer (2014) as cited in Hollberg and Ruth (2016), the architectural design process is divided into six stages, namely:

- *Preliminary Studies:* research, feasibility studies, and the definition of the project are realized.
- *Concept Design*: Basic architectural decisions, building orientation, and the massing of the building are made.
- *Developed Design:* Primary construction materials and building envelope are defined in a generic way. Design is refined, and geometry is finalized.
- *Technical Design:* Details are prepared, and technical specifications are defined.
- *Construction:* Realization of the designed project.
- *Use:* The building is handed over to the client.

Pre-design or concept design phase has the greatest influence due to its role in the definition of general conditions for the planning process and has the least cost for the design changes (Paulson Jr, 1976) (Figure 2.1). Thus, it is essential to have a decision support system in those stages to shape the important design decisions earlier. However, as indicated in the architectural design process stages, architectural detailing is prepared in the technical design phase, which results in almost no change in previously made early design decisions. Concerns such as building material selections and relations can only be assessed in later stages. To ensure that kind of system is also crucial considering environmental impacts and sustainability. As Basbagill et al., (2013) suggested: “the earlier decisions are made in the design process and the fewer changes to these decisions at later stages, the greater is the potential for reducing the building’s environmental impact”. To excel the expertise in the architectural design process in the early design phases of the building life cycle, it is necessary to understand the position of architectural detailing not only in the architectural design process but also in the approach of its way of dealing with the detailing problems, such as leading factors for the selection of detail, the relationship of macro and micro scales.

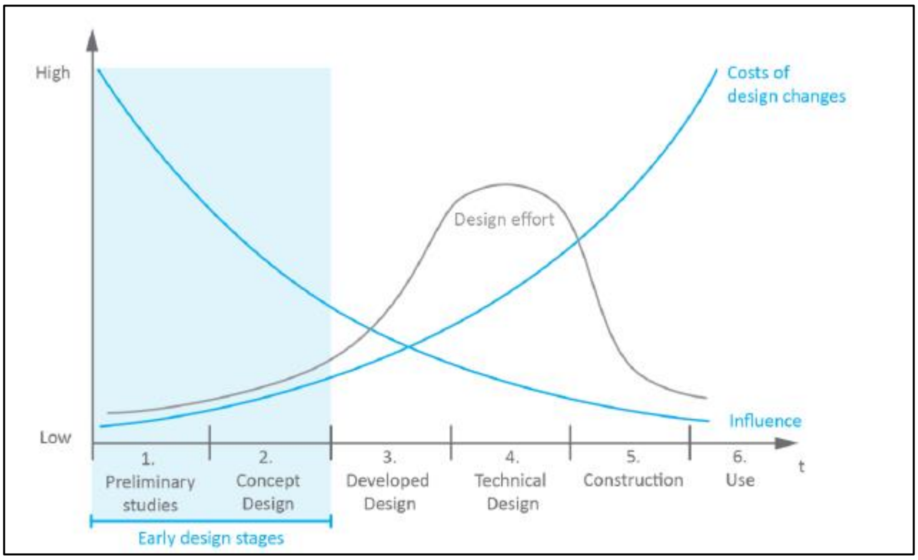


Figure 2.1. `Paulson curve` (revised version of Paulson Jr (1976) diagram, in the study of Hollberg (2016))

2.2 Detailing approach in architectural design

The importance of architectural detailing

A detail can be defined as a small part that is in relation to a larger whole, and it is architecture at its smallest size (Weber, 1991). Architectural detailing should be accepted more than a task-based decision-making activity because it is a knowledge-centered task. It boosts creativity in both the conceptual design phase and the development of the details themselves (Emmitt, Olie, & Schmid, 2004). Architectural details influence the characteristics of a structure, such as its aesthetics, quality, cost, and durability (Erbil, 2019). With a well-composed detail, the essence of the building design can be captured vividly, and the relationships between the parts of the building are clarified (Allen & Rand, 2016).

According to the study of Emmitt et al. (2004), architectural detailing can be performed with two main approaches; deductive and inductive. In the deductive approach, architects start with a big idea, and as the design develops, they direct their attention to the detailing. On the other hand, in an inductive approach, architectural technologists and architectural engineers start designing with the details and later formulate the conceptual design based on the developed details.

Architectural detailing should change over time to adapt itself to local building traditions, innovative technologies, and legislative frameworks (Emmitt et al., 2004). In that sense, in order to easily renovate a building and repair the details when necessary, it is important to propose a flexible system that enables changes in elements. This systematic approach will help to maintain sustainability and reduce the environmental impact of the buildings. To do so, architects need to evaluate how they design, detail, construct, use, reuse, and recycle the built environment (Emmitt et al., 2004).

To create a more environmentally friendly approach to the construction process, buildings should be constructed in a way that they are (i) easy to assemble, (ii) easy to maintain, (iii) easy to disassemble and recycle, and they (iv) have a minimal impact on the environment (Emmitt et al., 2004). However, designing a building is usually handled as a process that is finalized when the building is constructed. As essential stages of building life cycles, consideration of operation, maintenance, replacement, or refurbishment are needed to be well integrated into the design process.

The service life of the materials

Due to the fast-changing society with its unpredictable social-cultural, financial, and environmental needs, buildings are required to follow up on the developments (Paduart & De Temmerman, 2013). Existing building stock requires continuous investment for repair and renovations (Hovde & Moser, 2004). Moreover, buildings will be replaced with newer designs that are more in tune with the needs of future occupants (Aktas & Bilec, 2012). Hermans (1999) explained the reasons behind the building component changes over the building's lifetime as follows:

- *Structural parts*; their life span depends on the period of use of the building.
- *External building components;* such as roof and façade can be changed for maintenance and aesthetic face-lift.

- *Interior components;* the functional change of the building or the preference of the building user
- *Building services;* change generally depends on technological developments, technical deterioration, or changes in regulations.

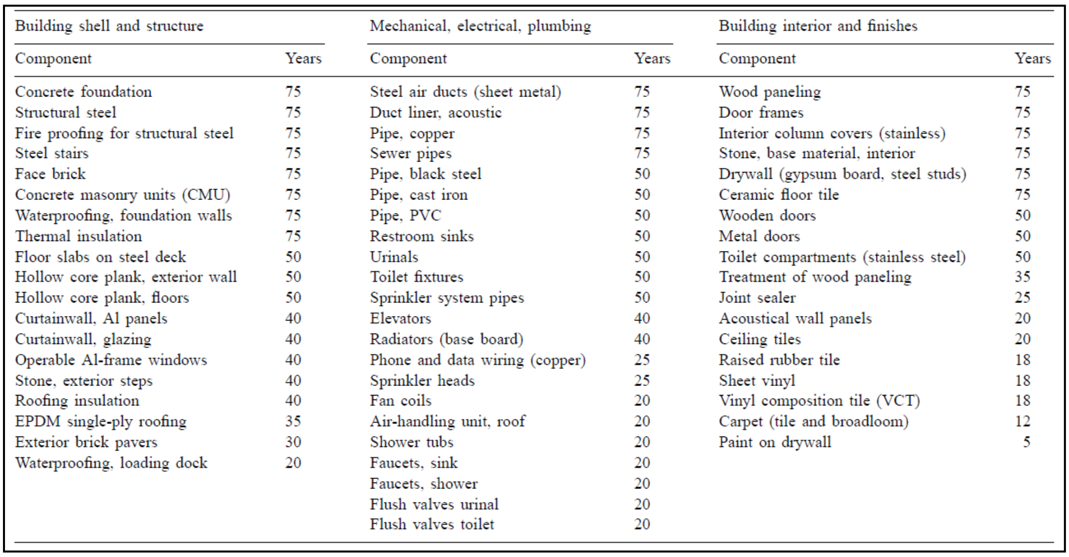
As an indicator of the determination of building condition during use, the service life of the building and building components are used. The service life of a building is defined as the "period of time after installation during which a building or its part meets or exceeds performance requirements" (ISO, 2011b). The service life of building components can vary based on degradation factors (agents) (Table 2.1). It is important to note that (i) numerous factors contribute to degradation, (ii) the significance of these factors depends on the material and geographic location, and (iii) information on the effects and extent of these factors is necessary to accurately predict service life (Masters & Brandt, 1987). The reference service life of building products should be reevaluated by accounting the several conditions such as indoor climate, outdoor climate, building function and use, design, execution, and maintenance and management (Straub, 2015).

Table 2.1. Degradation factors affecting the service life of building materials and components (Masters & Brandt, 1987)

Degradation factors	
Weather factors	Radiation Temperature Water Normal air constituents Air contaminants Freeze-thaw Wind
Biological factors	Microorganisms Fungi Bacteria
Stress factors	Stress, sustained Stress, periodic Stress, random Movement due to factors i.e. settlement or vehicles
Incompatibility factors	Chemical Physical
Use factors	Design of system Installation and maintenance procedures Normal wear and tear Abuse by the user

There are several studies that use the service life of building materials for different research purposes. To exemplify, the study of Scheuer, Keoleian, & Reppe (2003) aims to develop a life cycle model of a complex building and composes a reference list for the life span of materials in three parts: (i) building shell and structure, (ii) mechanical, electrical, and plumbing and (iii) building interior and finishes (Figure 2.2). Another study proposes a method to provide a common ground for the service life of building interior products. Accordingly, the lifetime of paint, carpet, hardwood, linoleum, vinyl, and ceramic are calculated respectively at 6.9 years, 10 years, 42 years, and 22 years (Aktas & Bilec, 2012). In the study of Treloar, Fay, Love, & Iyer-Raniga (2000), they analyzed the residential unit and defined replacement rates for a 30-year period. They listed the items required to be replaced or maintained periodically to extend the material/ product life such as paint, washing machine, space heater, and rainwater tank, which lasts respectively 10 years, 14 years, 25 years, and 30 years.

In addition to the service life information found in the articles in literature, multiple data sources were defined for the constitution of data model for the research as data by the US Census Bureau (Census, 2019), data by BEES v4.0 (Lippiatt, 2008), Environmental Product Declarations (EPDs) (EPD International, 2007) or important standards for service life as ISO 15686-1/2/7 and /8 (ISO, 2008, 2011a, 2012, 2017). The construction of service life information is limited because as stated in the study Straub (2015), although there is a need for systematic international data records of reference service lives of building components, they do not exist or are not publicly accessible. ISO 15686-1/2/7 and /8 (ISO, 2008, 2011b, 2012, 2017) define the service life information of building components and their importance for building construction. However, they do not provide any reference to the service life information of the buildings but rather explain a systematic methodology to predict the service life information under different circumstances.



Building shell and structure		Mechanical, electrical, plumbing		Building interior and finishes	
Component	Years	Component	Years	Component	Years
Concrete foundation	75	Steel air ducts (sheet metal)	75	Wood paneling	75
Structural steel	75	Duct liner, acoustic	75	Door frames	75
Fire proofing for structural steel	75	Pipe, copper	75	Interior column covers (stainless)	75
Steel stairs	75	Sewer pipes	75	Stone, base material, interior	75
Face brick	75	Pipe, black steel	50	Drywall (gypsum board, steel studs)	75
Concrete masonry units (CMU)	75	Pipe, cast iron	50	Ceramic floor tile	75
Waterproofing, foundation walls	75	Pipe, PVC	50	Wooden doors	50
Thermal insulation	75	Restroom sinks	50	Metal doors	50
Floor slabs on steel deck	50	Urinals	50	Toilet compartments (stainless steel)	50
Hollow core plank, exterior wall	50	Toilet fixtures	50	Treatment of wood paneling	35
Hollow core plank, floors	50	Sprinkler system pipes	50	Joint sealer	25
Curtainwall, Al panels	40	Elevators	40	Acoustical wall panels	20
Curtainwall, glazing	40	Radiators (base board)	40	Ceiling tiles	20
Operable Al-frame windows	40	Phone and data wiring (copper)	25	Raised rubber tile	18
Stone, exterior steps	40	Sprinkler heads	25	Sheet vinyl	18
Roofing insulation	40	Fan coils	20	Vinyl composition tile (VCT)	18
EPDM single-ply roofing	35	Air-handling unit, roof	20	Carpet (tile and broadloom)	12
Exterior brick pavers	30	Shower tubs	20	Paint on drywall	5
Waterproofing, loading dock	20	Faucets, sink	20		
		Faucets, shower	20		
		Flush valves urinal	20		
		Flush valves toilet	20		

Figure 2.2. The service life of the components in building system
(Scheuer et al., 2003)

The service life of buildings and their components should be determined at the initial stages of the design process. However, as explained before, it cannot be realized in the early stages due to the lack of common ground for the service life of the materials. If this information can be provided to the architects/designers at the beginning of the design process, awareness of the hierarchical relation of the building materials and its consequences would increase, which will contribute to circular design and sustainable development.

2.3 The need of circular construction

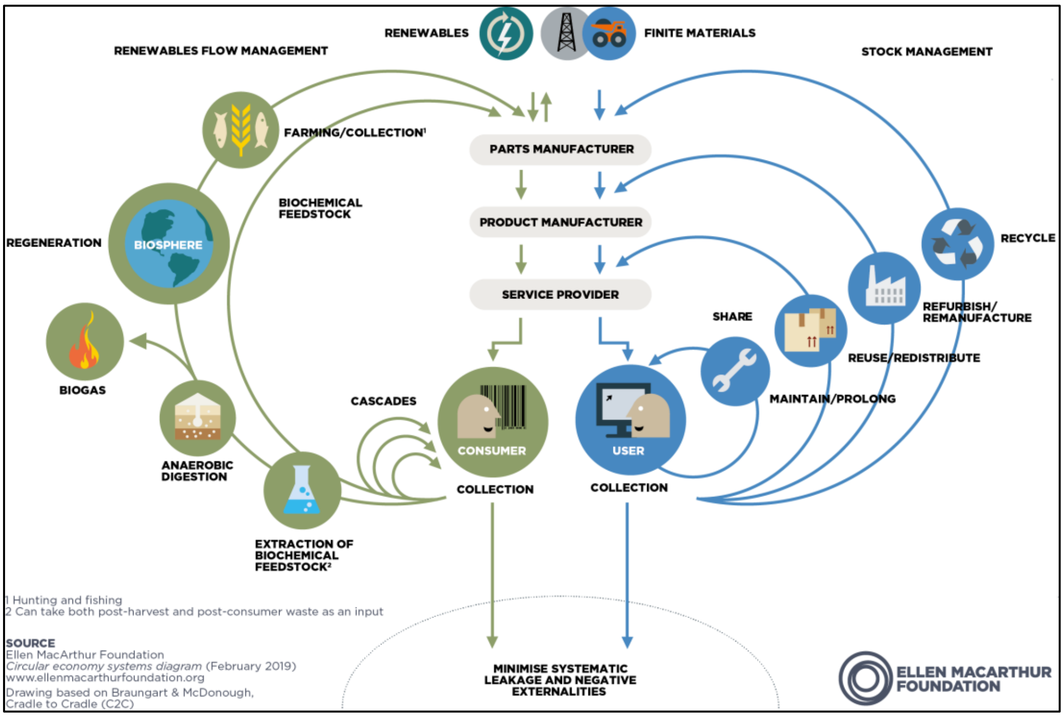
Buildings lead to serious environmental problems throughout their entire lifecycle, especially during the operation and end-of-life stages (López Ruiz, Roca Ramón, & Gassó Domingo, 2020). The reason behind this is mostly due to the generation of construction and demolition waste (CDW) and the manufacturing of building materials (Geng et al., 2017; Ghisellini, Ji, Liu, & Ulgiati, 2018). To diminish the demolition waste and overcome the environmental problems, it is necessary to enhance better management in the construction industry. The current linear economy model of “take-make-consume-dispose” creates environmental challenges and thus adapting new approaches and building strategies to reduce CDW has become a necessity (Poon, Yu, & Jaillon, 2004). In this context, it can be claimed that the transition to a Circular Economy (CE) would reduce environmental problems whilst contributing to economic growth (Lieder & Rashid, 2016).

2.3.1 Definition and aspects of circularity

The "Use and Throw" model of the linear economy was first reevaluated with the "Make, Use, and Re-Use" model in a report for the European Commission in 1976 (Stahel & Reday-Mulvey, 1981). With The Ellen McArthur Foundation, it gained increasing interest among researchers, governments, and different disciplines. Circular Economy can be defined as a model where products and components remain in the production cycle as long as possible (Ellen MacArthur Foundation, 2015). Ellen McArthur Foundation defined the idea of CE with three pillars:

- *preserve and enhance natural capital:* control over finite stocks and balancing renewable resource flows
- *optimize resource yields:* maintain the continuity of circulation in products, components, and materials
- *foster system effectiveness:* revealing and designing the system inefficiencies (McKinsey Center for Business and Environment, 2015).

Ellen McArthur Foundation created a circular economy system diagram, renowned as `the butterfly diagram`, which demonstrates the flow of materials with two main cycles: the technical cycle and the biological cycle. While the technical cycle includes the processes such as reuse, repair, remanufacture, and recycling for the long life of materials and products; the biological cycle includes circulations of biodegradable materials to the Earth (Ellen MacArthur Foundation, 2019) (Figure 2.3).



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 2.3. The butterfly diagram (Ellen MacArthur Foundation, 2019)

Circular economy in a built environment

The relationship between the built environment and the circular economy is a complex interplay that includes leading implications for sustainability and resource management. In the context of the built environment, the principles of the circular economy prioritize the efficient use of materials and resources within the building lifecycle. This approach is especially important when considering the problematic examples during the operational phase. The study of Çakıcı (2005) demonstrated the many dismantling processes in a residential building and presented the created waste and damage in these processes (Figure 2.4). Considering this, designing buildings based on a circular understanding with a sensitivity towards durability, adaptability, and disassembly to facilitate easy repurposing or recycling is a vital approach for a sustainable future.

As a key tool for achieving the circular economy, material passports are used in the management of material flows and decarbonization of the built environment (Hoosain, Paul, Raza, & Ramakrishna, 2020). Material passports are an active tool for tracking value and are designed to introduce residual value into the market (Luscuere, 2017). They include the datasets and reliable information including the entire value chain such as properties of the materials used, supply chain process ranging from the sources to producers, distributors, and consumers or users, and technical information for the improvement in the reuse or recycling of the materials (Hoosain et al., 2020). Material passports are not the ingredients list of the materials but also have contextual information related to material health, de-installation, material position, assembly, and disassembly (Luscuere, 2017). Lately, material passports have been combined with tools including BIM, Geo-information, and Unified building modeling (Hoosain et al., 2020). Although material passports provide contributions to improve material qualities with the current studies, there is still a need for further studies to evaluate material relationships and dependencies at multiple scales.

Figure 2.4. Damage from the dismantling process of a window (Çakıcı, 2005).

Moreover, in the current literature, there are relatively few research contributions focusing on the relationship between the circular economy and the early design process. Swift et al. (2017) studied the integration of RFID technology into building components to define ownership of components parts of buildings, with the aim of developing service management that checks the components` performance in need of an update or repair. Results of the study showed that this approach increases the potential of replaceable parts in buildings for adapting to user needs. Akanbi et al. (2018) developed a BIM-based whole-life performance estimator to evaluate the potential for reuse of the materials in the early design phase. The authors showed that buildings with steel structures, demountable connections, and prefabricated assemblies are the ones with the most reusable components. Akanbi et al. (2019) propose a Revit plug-in for the analysis of the disassembly and deconstruction capabilities of the materials in the design phase. The study presented that BIM software can provide information for assessing the performance of building designs with respect to the circular economy principles.

In addition to the relationship between the circular economy and the early design phase, Life Cycle Assessment can be considered as a valuable tool for assessing the environmental and social impacts of circular practices to achieve more sustainable, resource-efficient systems. Circular economy and life cycle assessment are closely related. While circular economy suggests closed-loop systems to minimize waste and to manage resource usage, life cycle assessment evaluates the processes of a product throughout its life cycle, from raw material extraction to end-of-life scenarios (disposal/ recycling). The intention is to support the closed loop to decrease the environmental impacts of the processes. Therefore, life cycle assessment can be used as a useful implementation tool in the circular economy, enabling the process planning of the products/ buildings.

2.3.2 Life cycle assessment

In many countries, the construction industry contributes to socio-economic development and has a large share in the consumption of energy and natural resources. Significant measures have been implemented to reduce the operational energy usage of buildings, with the introduction of numerous international protocols and national regulations in recent years. In addition to that, it was shown that further improvements for decreasing primary energy demand lie in reducing the embodied energy of buildings (Hollberg & Ruth, 2016). LCA is an important tool both to account for the embodied energy involved in a product or a system, and to measure the environmental impacts of materials (Asif, Muneer, & Kelley, 2007). Although building material manufacturers examine individual construction materials or building components and publish environmental product declarations (EPDs) to supply the environmental impact data, such an assessment may be misleading due to the lack of certain inputs. Considering this fact, it is plausible to state that the most reliable form of LCA in the construction industry is the "whole-building life cycle assessment", in which a building is examined entirely over all stages of its life cycle (O`Connor & Bowick, 2014). The scale and scope of the analysis in the whole building LCA are different from those of other industries. The entire building and all its constituent parts, including many material flows and component installation processes, are examined in a whole building LCA. These processes are categorized by Hollberg and Ruth (2016) into four main stages: product, construction, use, and end of life, the breakdown of which is given in Table 2.2.

Table 2.2. Whole building LCA life cycle stages (Hollberg & Ruth, 2016)

Product	Construction	Use	End of Life
A1 Raw Materials Supply	A4 Transport	B1 Use	C1 Demolition
A2 Transport	A5 Construction	B2 Maintenance	C2 Transport
A3 Manufacturing		B3 Repair	C3 Waste Processing
		B4 Replacement	C4 Disposal
		B5 Refurbishment	
		B6 Operational Energy Use	
		B7 Operation Water Use	

Standards regarding life cycle assessment

After gaining interest in multiple industries, the methodology of LCA was defined by the International Organization for Standardization ISO 14040 series (ISO, 2006). These series include four steps of an LCA study; goal and scope definition and inventory analysis (ISO, 1998), life cycle impact assessment (ISO, 2000a), and life cycle interpretation (ISO, 2000b). As demonstrated in Figure 2.5, ISO 14040 describes the general life cycle assessment framework whilst the standards mentioned above define the detailed information for each step. ISO 14041 defines *(i)* goal and scope definition, including the information about the assumptions, the system boundaries, purpose, and objectives of the study, and *(ii)* life cycle inventory analysis (LCI), including the information regarding the data collection to satisfy the study`s aims (ISO, 1998). ISO 14042 expresses the life cycle impact assessment (LCIA) that evaluates a system`s (product) LCI results to understand the impact on the environment (ISO, 2000a). ISO 14043 explains the discussion of the results of LCI and LCIA to develop the outcomes for decision-makers (ISO, 2000b).

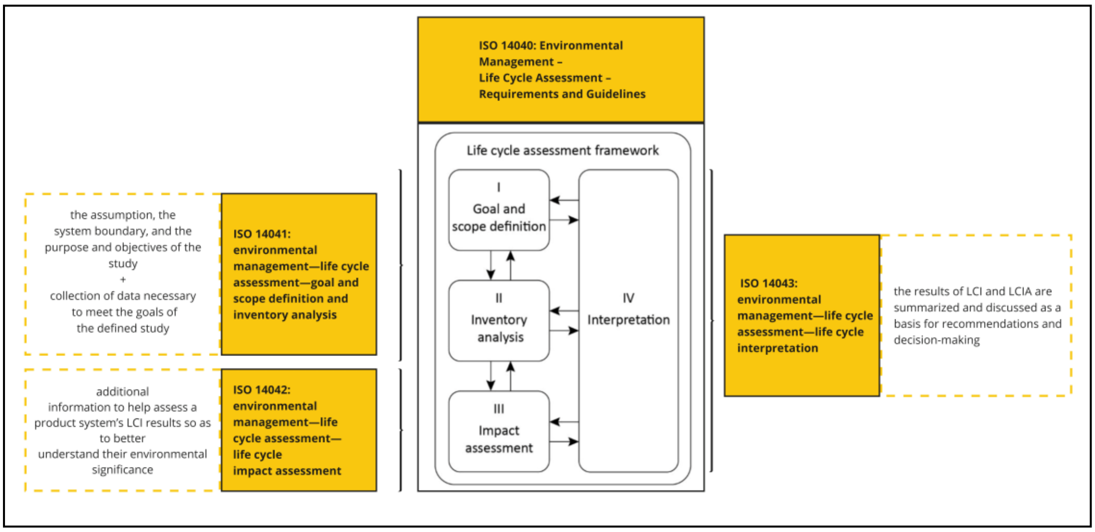


Figure 2.5. Life cycle assessment methodology in ISO standards

While ISO 14040 series describe the methodology of LCA studies, European standards for LCA of buildings, EN 15804: 2012 and EN 15978: 2012, classify the life cycle of buildings and building products in five steps. They are Product (A1-A3), Construction (A4-A5), Use (B), End-of-life (C), and an additional stage for benefits beyond the system boundaries (D) (EN, 2012a, 2012b) (Figure 2.6). Product Stage (A1-A3) includes the definition of the production of materials until the gate of the manufacturer, which is referred to as cradle-to-gate analysis (Hollberg, 2016). If the circle of construction, use, end-of-life, and benefits is completed considering the life cycle of buildings, it is referred to as cradle-to-cradle.

The life cycle modules of a building are described in EN 15978 standard, with the phases in detail (EN, 2012b). Although the framework of life cycle assessment in buildings is constructed considering the whole life span of the building, the system boundaries of the buildings change according to the study scope (Figure 2.6). Benefits (D) module includes the definition of system boundary based on the importance of processes in building construction. Cut-off criteria have to be chosen and documented to define system boundaries. The percentage contribution of the individual product to the whole system is calculated to understand the significance by measuring the mass, energy, or environmental impact (Hollberg, 2016).

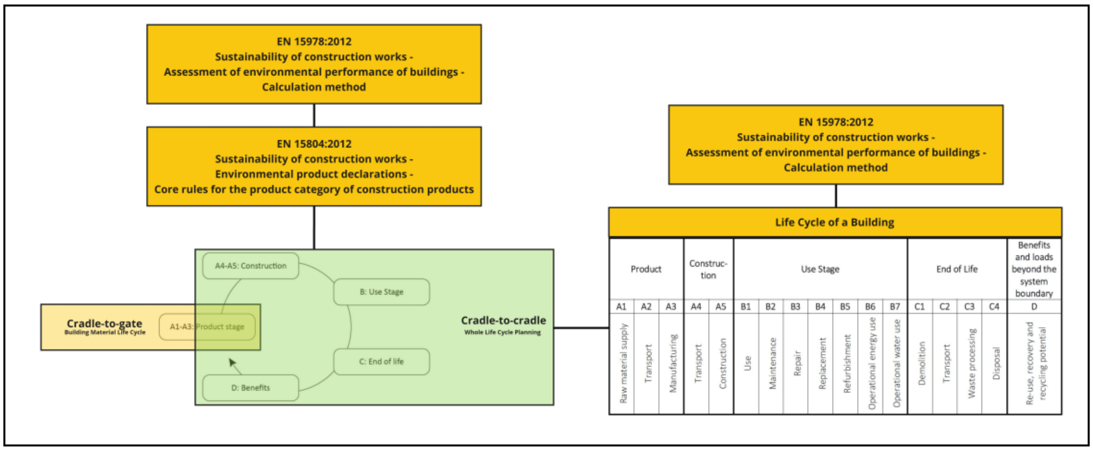


Figure 2.6. Life cycle modules of buildings in EN standards

2.4 Learning from the cross-industries

In the era of technology, boundaries between the disciplines are blurred, and the adoption of technology, systems, or approaches from other disciplines has become a common practice. Although producing assets in diverse fields may have different requirements due to their contexts, the core work is production. The terms used for production vary depending on the discipline, and the most widely recognized ones are manufacturing and construction. Just as a building is admitted as the outcome of construction, products are the outcomes of manufacturing.

2.4.1 The life cycle of a product

The term ‘lifecycle’ can be defined as “the whole set of phases, which could be recognized as independent stages to be passed/followed/performed by a product, from its cradle to its grave" (Terzi, Bouras, Dutta, Garetti, & Kiritsis, 2010). The product life cycle includes three main phases and data available in each phase: *(i) Beginning-of-Life (BOL)* includes processes related to design, development, production, and distribution, (ii) Middle-of-Life (MOL) consists of processes related to a product's use, service, maintenance and repair, (iii) End-of-Life (EOL) includes the processes related to reverse logistics such as reuse, recycle and disposal, remanufacturing (disassembly, refurbishment and reassembly) (Esmaeilian et al., 2018; Kiritsis, 2011; Wuest, Hribernik, & Thoben, 2015) (Figure 2.7). The relation between these three phases does not have to be linear. According to the study of Jun, Kiritsis, & Xirouchakis (2007), the whole product life cycle has complicated flows of information, and they define different relationships between themselves during the life cycle of a product.

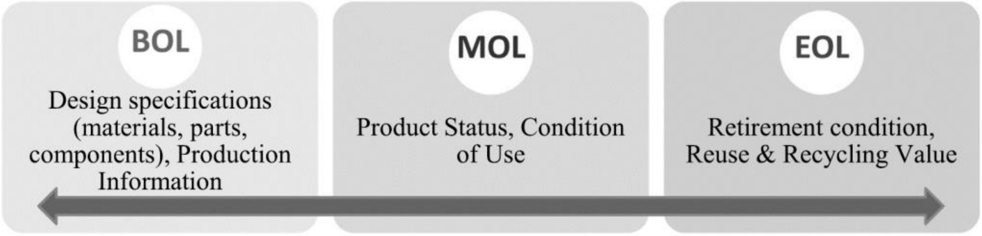


Figure 2.7 Three main phases of the product lifecycle and data available in each phase (Esmaeilian et al., 2018)

2.4.2 Detailing understanding

Products have a high level of complexity that requires numerous processes and assemblies throughout the life span. In the realm of manufacturing, where precision is outstanding and the path to excellence is a need, the significance of detailing cannot be overemphasized. The grounds of quality, efficiency, and safety depend on attention to detail. Details in manufacturing provide solutions for changes in user needs, technological developments, or unforeseen needs in the future. A single millimeter can define the success of a mission in the aerospace sector whilst precision engineering provides performance and safety in the automotive industry.

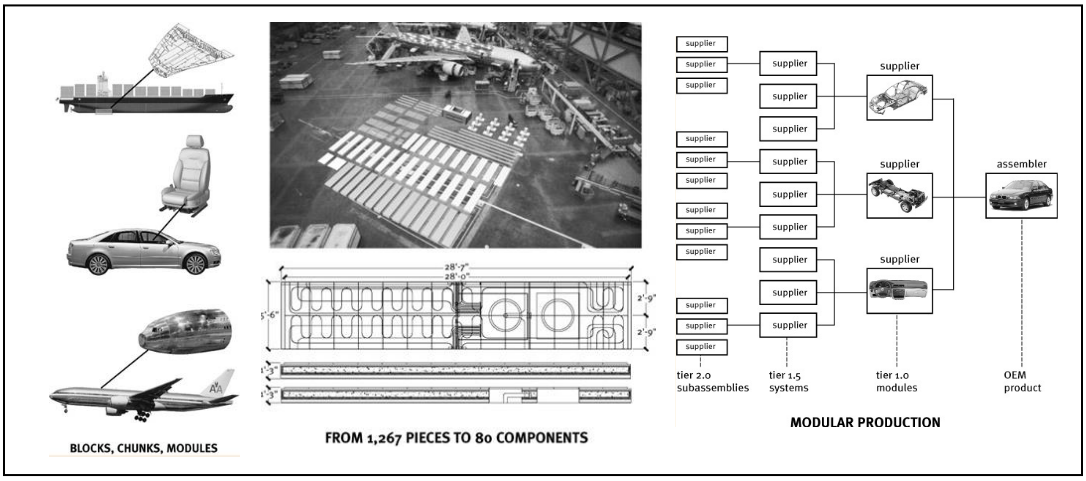


Figure 2.8. From pieces to components in the automobile and Boeing aircraft industries (Kieran & Timberlake, 2004)

The change in detailing understanding can lead to the emergence of new business models and new requirements in various disciplines. To illustrate, till the mid-1980s, Japanese brand Seiko was producing quartz-powered digital imports that were cheap to produce and sell when compared to Swiss watches (Rossen, 2019). In the traditional manufacturing side of the watch industry, a watch requires the classical division of parts, including the bottom plate, case, and case back. At that time, ETA SA, a Swiss company that produces watches and was led by Ernst Thomke, developed a model that includes fully integrated production, in which all components are assembled on one plane and directly in the watch case (Swatch, n.d.). That change in detailing understanding resulted in the rise of Swatch watch technology since it was both durable and inexpensive (Rossen, 2019).

Along with the change in detailing understanding, Industry 4.0 led to a paradigm shift in production processes, from centrally controlled to decentralized by providing communication between people, machines, and resources (Hermann, Pentek, & Otto, 2016). This resulted in a rise in new production techniques to manage production effectively with the help of detailing considerations. Considering the fact that there are roughly 4.000 parts for a car, 1.000.000 parts for a Boeing 777, and millions for a large ship, a new manufacturing system aimed to solve the problems in the assembly processes of these high number of pieces. It adopted non-gravity-based processes where pieces of the objects are grouped and created chunks/blocks. These chunks were brought together only at the final assembly to create the whole (Kieran & Timberlake, 2004) (Figure 2.8).

Table 2.3. Overview of design strategies to slow resource loops (Bocken, de Pauw, Bakker, & van der Grinten, 2016).

Designing strategies to slow loops
Designing long-life products
- Design for attachment and trust - Design for reliability and durability
Design for product-life extension
1. Design for ease of maintenance and repair 2. Design for upgradability and adaptability 3. Design for standardization and compatibility **4.** Design for disassembly and reassembly

With the increase of resource efficiency and sustainability understanding in production, manufacturing pioneered the adaptation of business models in terms of principles of circular economy. As each product has a life span, the range of various phases and their interrelations may change with the design strategies that contribute circular economy. According to the study of Stahel (2010), these fundamental strategies are managed with the cycling of resources in product design *(i)* slowing resource loops: through the design of long-life goods and product-life extension *(ii)* closing resource loops: through recycling. Slowing resource loops down is important to manage produced waste by changing the life cycle of products/components and materials. In order to slow resource loops down, there needs to be changes in design approaches for product manufacturing. Bocken et al. (2016) demonstrated the typical design strategies to slow resource loops down (Table 2.3). As an example of the adaptation of circular design strategies, FairPhone, which is one of the leading companies to offer their users to repair and replace broken parts, can be named. With this modular phone, users were able to repair it instead of replacing it (Pesce, 2015) (Figure 2.9).

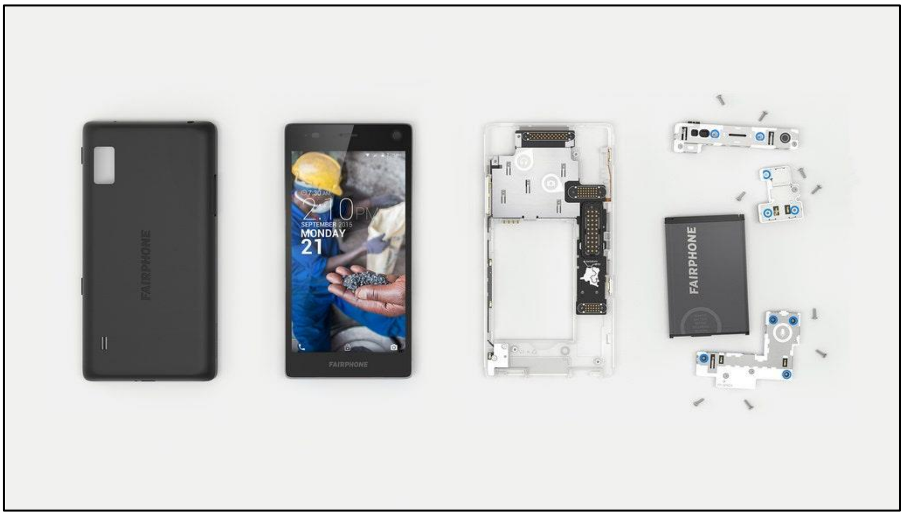


Figure 2.9. FairPhone example for design for ease of maintenance and repair (Pesce, 2015)

2.4.3 Main implications from the cross-industries

The manufacturing industry welcomes and adopts new design strategies and production techniques reevaluating detailing approaches. The industry reaches its aims with the change in manners, techniques, and approaches in terms of detailing. The main implications from the cross-industries provide the construction industry learning and gaining new perspectives for the existing problems. Accordingly, the main implications from previous paragraphs can be compiled as follows:

1. *Integration of new detailing understanding to transform the production technique:* The manufacturing field introduces new detailing relations such as integration of modular parts, change in assembly relations, and new production techniques.
2. *Arise in circular design and life cycle thinking:* Designers have an ever-growing emphasis on circular design principles and life cycle thinking in product design. With this transformation in design philosophy, a product is not a single unity but is part of a larger ecosystem that addresses the questions of resource efficiency and waste reduction.
3. *Integration of technological advancements:* Industry 4.0. revolutionized the cross-industries by technological advances that have paved the way for

business models and production techniques. Once there is an opportunity to design the process, designers could develop innovative solutions for the relations as connections, sequences, and edges.

2.5 Addressing the problems in the building process

As a dynamic and ever-evolving industry, the construction industry faces many challenges and obstacles in handling the intricacies of building projects. In that sense, the ability to identify and address these challenges is a necessity to overcome the potential and existing problems. This study evaluates the building process in construction and reveals the existing problems both in light of the lessons learned from other industries and the literature review. Accordingly, the problems in the construction industry in the scope of this study are compiled as follows:

1. *The lack of information in the early design phase:* Although the early design phase is the most influential phase for decision-making, there is a lack of guidance for that phase.
2. *The lack of understanding of detailing design:* The detailing understanding in the construction industry mostly depends on the functional and aesthetic decisions that are to meet the requirements in the design program. However, buildings are structures that have been used for long periods. It is required to examine the relation between the whole (building) and the parts (building components) with respect to the service life to provide the beneficial life cycle.
3. *The lack of circular design understanding:* Although circular design principles gained interest in the theory, there are still bottlenecks for the application of these principles in practice. Therefore, there is a need to apply these principles to the construction industry and develop business models/strategies that consider material recoverability, repair, and end-of-life scenarios.
4. *The uncertainty of boundary definition in life cycle assessment studies:* While integrating the life cycle research into building design, the researcher is

required to define the system boundary. It diminishes the proximity between simulation and real building performance because building life cycle phases are part of a system (building process), it is much more realistic to evaluate the building life cycle phases as a whole instead of slicing the process.

Based on the indicated problems in the construction industry, a new strategy that proposes an architectural detailing assessment interface in the early design process is necessary to provide solutions to them. Accordingly, this research is intended to provide a feedback mechanism for architects that will contribute to material efficiency and effective maintenance. This proposal will pave the way for a circular and sustainable design process that enables the control of the process during the whole life cycle of the building from early phases to end-of-life.

CHAPTER 3

BUILDING AS A SYSTEM

> “All buildings are predictions,
> and all predictions are wrong.”
> *(Stewart Brand)*

The built environment is a complex system that includes interconnected layers, each serving a purpose within the overall. A system perspective approach has emerged and is widely utilized to comprehensively understand the dynamic relations and dependencies among buildings’ various components. Understanding the artifacts as systems brings about several considerations across different fields In architecture, this is referred to as system structure, while in production, it is known as product architecture. Although both terms are used to describe the decomposition of systems in different fields, the decomposition levels and approaches differ within each field. Cross-industry learning is crucial for developing systems thinking; therefore, the concept of product architecture should be examined and discussed with regard to its implementation in architectural compositions. When considering the system structure of architectural compositions, different approaches exist for decomposing the building structure into levels and layers. The approach, which perceives building as a combination of levels and layers, embraces the recognition of every detail of design with its own purpose. Such perspective is crucial for the stakeholders of the construction industry such as architects, engineers, builders, and users, as examining building layers/levels can pave the path for forming adaptable building structures to respond to the evolving needs and contextual factors that arise or change over time. In addition to the decomposition from whole to parts, it is important to understand how to evaluate the relationships and dependencies between the building layers and levels to guide the architectural design process with a methodological approach, specifically using the Design Structure Matrix within the scope of this thesis. In this context, it can be claimed that the nexus between building layers/levels, system theory, and architectural design may ground the base for adaptable and transformable building structures.

While the theoretical approaches and aims regarding the decomposition of building structures create insights for developing the adaptability of building structures, building decomposition data in information technologies results in the development of digital tools and building classification systems. As a unified method of various types of data, the Industry Foundation Class is useful for understanding geometric and semantic information of building structures, providing a structured classification system, and enabling detailed descriptions of relations between components in digital platforms. In addition to the reflections of decomposition understanding to the digital tools, it is also crucial to understand the current conditions of digital design tools and their capabilities in terms of the systematic evaluation of building structures and the implementation of decomposition approaches with them.

In that context, this chapter delves into the approaches considering building as a whole (systems thinking) and building as a combination of layers/levels (decomposition of the building). The reasons for change over time, the need for adaptability in building components, and the means of decomposition in buildings to reveal the physical and semantic relations in the building system were elaborated. The application of building decomposition understanding to digital mediums, and management tools of such systems were presented.

3.1 Designing with time

In today's world, architects face a new challenge: designing for the unknown, the unpredictable (Leupen, Heijne, & van Zwol, 2005). The needs of society are changing in each era. Even during the lifetime of a person, the personal needs are continuously changing. Change is only a constant factor and it is becoming more and more unpredictable over time. If unpredictable change is a constant factor, there arises a necessity for certainties that require changeability for accommodating the ever-changing patterns of use (Bijdendijk, 2005). Throughout the operational phase of buildings in the long run, they are required to change and transform themselves based on predictable needs such as maintenance and repairs, and unpredictable needs such as newly adopted functions, and upgrades- especially via technology. The need for change may even be affected by the social and political movements in human history such as the oil crises in the 1970s, as explained by Brand (1995):

> “After the 1973 oil crisis, the energy budget of a building suddenly became a major issue, and windows, insulation, and heating and cooling systems had to be completely revamped towards energy efficiency.” (p.13)

Accordingly, considering the terms of adaptability on many levels is a need that should not be overlooked while developing the built environments. Building adaptability has a wide range of definitions based on the different applications in multiple scales. In general, it can defined as “the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing value through life” (Schmidt III, Eguchi, Austin, & Gibb, 2010, p.235). The changing needs are inevitable throughout the lifecycle of buildings, and they should respond to the arising needs of their users. Any changes in needs over time should be accommodated by buildings through having the capacity for modification and adaptation. To facilitate this, adaptability and changeability understanding in building structures involves developing strategies to extend the longevity of the building/product by allowing it to adapt to changing circumstances. Such strategies focus on the management approaches for the building systems, building components, and their relations.

3.1.1 An adaptability measure: Changeability

In any system, the design of system architecture faces two challenges to maintain the system throughout its life cycle: *(i)* system architecture has to have the property of being changed easily and rapidly, and *(ii)* system architecture has to have the feature of being sensitive and adaptable towards changing environments (Schulz, Fricke, & Igenbergs, 2000). Systems incorporating an architecture should support the changes throughout their useful life. As any system belongs to higher systems (system of systems) as well as belonging to a human response system (users and their needs), the feature of adaptation to changing circumstances is a necessity in any type of system architecture (Fricke & Schulz, 2005). Based on this understanding, the researchers coined the term `Design for Changeability (DfC)` and described it as:

> “DfC focuses on incorporating changeability into a system’s architecture in order to enable for foreseen and unforeseen changes within the architecture throughout the systems lifecycle, which could include using an existing architecture for possible derivatives” (Fricke & Schulz, 2005, p.346).

DfC is defined by four aspects of changeability: robustness, flexibility, agility, and adaptability; which depend on three basic design principles: ideality (simplicity), independence, and modularity (encapsulation) (Fricke & Schulz, 2005), as illustrated in Figure 3.1. These principles can be found in any system as a single entity or in the form of interrelations between each other. The important thing is that, regardless of the system type, the design of its architecture depends on the system`s elements, their attributes such as functions and properties, and their relations (Fricke & Schulz, 2005). Providing a combination of these principles may foster the system architecture or shadow each other`s effects on the system. Therefore, the selection of these principles, their combination, and their degree are crucial considerations in the evaluation of a system architecture. When contemplating the diverse change requirements of the various components within a building, it is crucial to deliberate on the extent to which changeability should be incorporated into the overall system architecture. It is important to assess the system within the design for changeability framework thoroughly and to question the system’s characteristics, the necessary degree of changeability, and the type of changeability required.

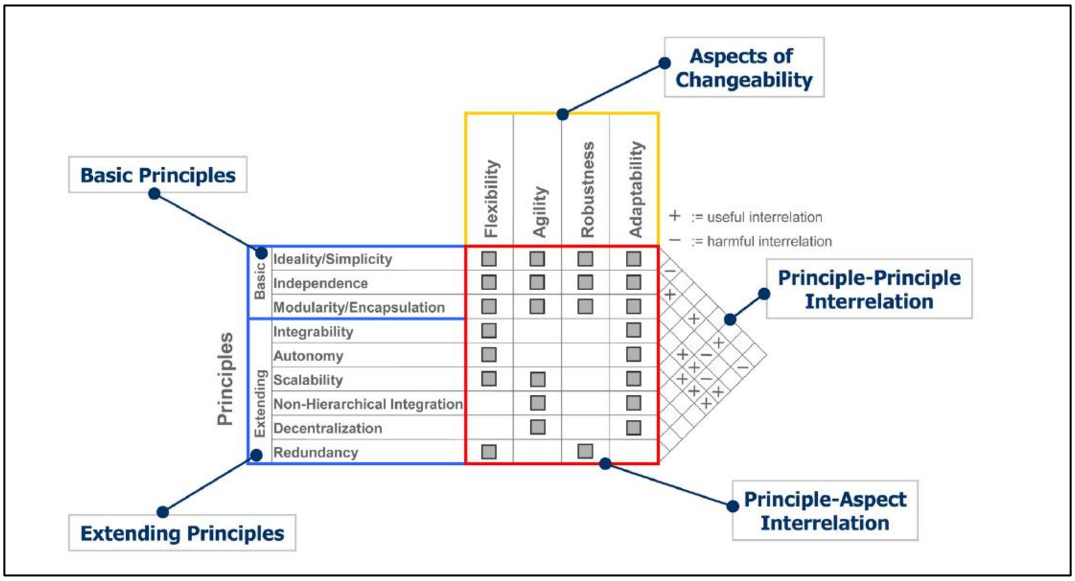


Figure 3.1. Design for Changeability framework (Fricke & Schulz, 2005)

3.2 Systems thinking

Evaluating complex systems by adopting a holistic approach before decomposing them into manageable individual components is a prominent design strategy that prioritizes effective operation throughout a building's lifetime. This understanding recognizes that the overall system or structure embodies relationships that provide valuable insights into patterns and functions. Embracing a whole-to-parts mindset is particularly prominent in fields such as systems engineering, architecture, and ecological studies, where the interconnectedness of elements profoundly influences decisions regarding efficiency, functionality, and sustainability. More efficient problem-solving and decision-making processes in building design may be achieved with systems thinking and revealing interrelationships.

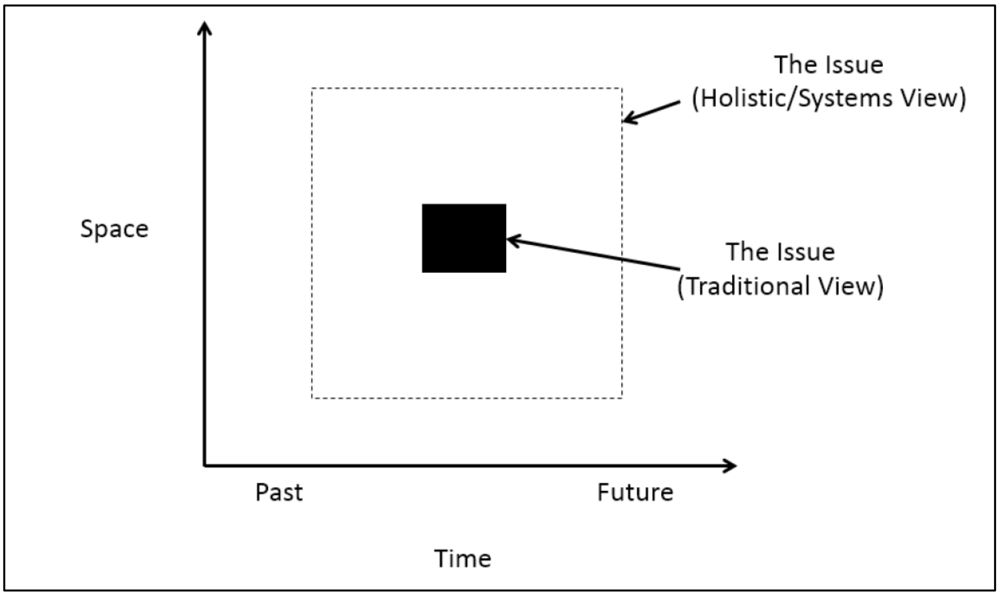


Figure 3.2. Systems thinking vs traditional thinking (Monat & Gannon, 2015).

A system is "a cluster of interrelationships with internal flows of information, forces, and material" (Bachman, 2003b, p. 18). Although every system has its own property, system characteristics can be explained with some common grounds. According to the report of Kim (1999), systems characteristics are as follows:

- *systems have a purpose:* every system has a purpose that describes it as an individual entity and provides integrity to hold it together.
- *all parts must be present for a system to carry out its purpose optimally:* every part is connected to another, and the nature of the system changes if a piece is added or removed from the system.
- *the performance of a system is affected by the order in which the parts are arranged:* the order in the system cannot be random, and the assembly of the parts matters in systems.
- *systems attempt to keep up stability with feedback:* Feedback fed the system with the information to stabilize the efficient system working.

The general system theory was developed by the biologist Ludwig von Bertalanffy in the 1940s to address the complexity of living systems with a new approach. It is "a new worldview that emphasizes key concepts as every system's embeddedness in other, larger systems, and the dynamic, ever-changing processes of self-organization, growth, and adaptation” (Montuori, 2011, p.414). It emerged as an alternative way of thinking towards the reductionist (analytic) understanding which fails to examine the wholes, interdependence, and complexity (Montuori, 2011). In such an understanding, a complex structure is evaluated from an isolated, classified perspective which is unable to evaluate the systematic properties, or relationships, and interactions that form the organization of life (Montuori, 2011). Unlike the reductionist understanding, systems thinkers study the complex patterns of connections between components to understand the behavior of the whole, and these web-like patterns cannot be analyzed with the evaluation of single parts (Gardner, Olney, Craven, & Blackman, 2019). According to Braithwaite et al. (2017, p.5), the essence of systems thinking can be explained as:

> “Reducing a system to its component parts is like inspecting the legs, body, neck, and head separately and expecting to understand how a giraffe works. Instead of pursuing such reductionism, complexity scientists aim to study the properties and characteristics of the system.”

Systems thinking is holistic (integrative/system) thinking instead of analytic (dissective/reductionist/traditional) thinking. In the last two centuries, scientific research has used reductionist thinking since it divides complex situations into smaller pieces to analyze them. Although this approach has some benefits, it ignores the relationships between system components and system behavior. Systems thinking presents how problems are understood and how people and resources are engaged in such processes (Gardner et al., 2019). It is a holistic approach that both involves spatial and temporal elements -time-. It includes a vision of the future and the consequences of the past (Monat & Gannon, 2015) (Figure 3.2).

System thinking is different than traditional thinking in some aspects. The main differences have been illustrated by several different organizations. A comparative table from the Australian Prevention Partnership elaborates on the differences between the problem definition and problem-solving process ((Australian Partnership Prevention Centre (2019) as cited in Gardner et al. (2019)) (Table 3.1).

In summary, systems thinking is *(i)* a method of arranging observations, *(ii)* a method of considering the related objects and processes, *(iii)* a method of defining the parts (components) of a system, *(iv)* an outcome from systematically thinking systematic phenomena (Kesik, n.d.).

Table 3.1. Traditional thinking and systems thinking
((Australian Partnership Prevention Centre (2019) as cited in Gardner et al. (2019))

	Traditional thinking	**Systems thinking**
How a problem is explored	Isolate parts to understand the behavior	Explore the emergent nature of the system as a whole
Aim	Create a solution to solve the problem	Deepen understanding of the system and identify a response to test
Nature of the problem	Can be defined and isolated, with a clear cause and a solution. Problems can be understood objectively	A situation has multiple causes, with no clear single solution. Wicked problems are understood differently depending on the perspective
Who is responsible for the solution?	External/others	Everyone is a part of the system and therefore needs to engage in change
How solutions are achieved	Multiple short-term success leads to long-term solutions	Most action has unintended consequences. Need to test, seek feedback, and adapt responses
How the problem can be solved	Improve parts to improve the whole	Improve the whole through improving the relationships between parts
Problem-solving process	Linear process with clear steps, start and finish	Multiple entry points, a non-linear process focused on learning and iterating

Systems thinking is utilized in multiple disciplines as an alternative thinking way to develop solutions to problems. In building science, system theory is used to understand the complex relations and behavior of the building structures. The basic characteristics common to all systems are significant to remember when applying system theory to building science:

- *Boundaries and boundary criteria:* A building is a complex structure that includes multiple sub- and supra-systems and does not end at the outer surface of its enclosure. The relationship between basement flooding and municipal sewer surcharge is an example of that systems` relation.
- *Flows and storage:* There are several information input-outputs and storage ways in building systems such as inhabitants, energy, water, sewage, and data.
- *Transformations:* As buildings age, it is desirable to design buildings that enable adaptations to new needs such as technological advancements, changing user needs, or trends.
- *Spatial and temporal hierarchies:* Reaching secure building design and passive survivability are important considerations to increase spatial and temporal resilience by providing the maintenance of vital functions.
- *Feedback and control loops:* Control over the indoor environment and maintaining safety and security are achieved with the management of efficient human-building interaction and its responses (Kesik, n.d.).

The introduction of the systems approach in the 1960s also coined the approach `the building as a system concept`. The building as a system approach outlines the primary elements comprising the system to be used in the considerations of relations in the design phase. According to that, the building system can be categorized as:

- Building enclosure (building envelope system)
- Inhabitants (humans, animals, and/or plants, etc.)
- Building services (electrical/mechanical systems)
- Site, with its landscape and services infrastructure
- External environment (weather and micro-climate) (Kesik, n.d.).

Although systems thinking improves the understanding of building elements as a system and changes how designers approach the design problem, it is still in progress in terms of formulating the regulations, standards, and construction processes. Since there is a narrow understanding of the complex and dynamic inter-relationships between objectives and outcomes, complex systems in the built environment are prone to failure in operation (Shrubsole, 2018). The limited research studies systems thinking for possible solutions; to address the decarbonization in the complex system (Davies & Oreszczyn, 2012); to overcome the performance gap problem in construction (Shrubsole et al., 2019); and to improve the urban governance for better cities in future (Orr, 2014). It is important that the insufficiency in current models and ways of thinking should be recognized for capturing the diverse complexity of the built environment and adapting to the potential changes.

3.3 Systems architecture

Architecture is “the structure - in terms of components, connections, and constraints - of a product, process, or element” (Maier & Rechtin, 2000, p.297). It is a way to depict the components of a system and the communications between them. Systems are constrained to conform to architecture (Luckham, Vera, & Meldal, 1995). The term `system architecture` is mostly used in information systems to describe the structure, interaction, and technology of computer system components (Burd, 2010). In the scope of this thesis, systems architecture is used as a high-level structure and organization of a complex system to express its components and relationships. In many fields, systems architecture is handled and described differently in terms of the scale and the scope of the field, such as `product architecture` in the production field and `systems structure` in the architectural field. A system structure focuses on how a building can be decomposed into components that adjust the way buildings are produced. The main aim of a system structure is to establish a connection between early design decisions and the construction phase of buildings (Vibæk, 2014). On the other hand, product architecture indicates a static physical structure of the elements of a product. There is a need for a supply chain embodying decisions about the flow of processes, materials, and operators to reach the final product (Vibæk, 2014). In such end, while system structure is utilized in the architectural field, product architecture is focused on the production field; and this distinction in scales brings about the various considerations related to structural compositions within each field. As system structure addresses the buildings on a larger scale, a product architecture approach is necessary to examine relationships, such as architectural details, on a smaller scale. The following section delves into definition of product architecture within the realm of the production field, as understanding the similarities and distinctions between fields may inspire the development of novel strategies and approaches. It then progresses to explore different approaches to building decomposition through diverse studies.

3.3.1 Product architecture

Product architecture is “the scheme by which the function of a product is allocated to physical components” (Ulrich, 1995, p.419). The product architecture includes information on how many components the product has, how these components work together, how they are made and combined, how they are utilized, and how they are disassembled, especially in complex mechanical and electromechanical products (Fixson, 2005). It is a method to structure a system composition and interactions between components (Schmidt III, Deamer, & Austin, 2011) and it is used for *(i)* the organization of functional elements; *(ii)* the mapping from the functional elements to physical components; and *(iii)* the qualification of the interfaces among relating physical components (Ulrich, 1995).

The physical elements of a product are organized into the major physical building blocks, that is called `chunks`. Each chunk consists of a collection of components that realize the functions of the product. The architecture of the system is an arrangement of the functional elements into these physical chunks and their interactions (Ulrich & Eppinger, 2012). A key characteristic of a product architecture is the extent to which it is modular or integral. While modular architectures have physical chunks that are related to a specific set of functional elements and well-defined interactions with other chunks, integral architectures involve the dispersion of functional elements across chunks and ill-defined interactions between the chunks (Ulrich & Eppinger, 2012).

Modular architectures are classified as:

- *Slot-modular architecture:* each interface between chunks is a different type from the others resulting in no change options between them.
- *Bus-modular architecture:* physical chunks are connected to a common bus component.
- *Sectional-modular architecture:* all interfaces are the same type, but there is no single element that other chunks could attach (Ulrich, 1995).

Differentiation related to architecture types is demonstrated in Figure 3.3. Accordingly, a product, i.e., a desk, can include common functional and physical characteristics in the chunks having integral architecture or may consist of chunks having modular architecture. This modular architecture can generate the possible changes and different combinations with six modular operators which are *(i)splitting* a design (and its tasks) into modules, *(ii)substituting* one module design for another, *(iii)augmenting* adding a new module to the system, *(iv)excluding* a module from the system, *(v)inverting* to create new design rules, and *(vi)porting* a module to another system (Baldwin & Clark, 2000).

Ulrich & Eppinger (2012) suggested a four-step method for the organization of product architecture. Accordingly, a product schematic is developed, and its elements are clustered into chunks. The geometric layout is then studied in 2D or 3D dimensions. Finally, fundamental and incidental interactions are revealed through schematic analysis, interaction graphs, and a structure matrix, particularly for more complex products.

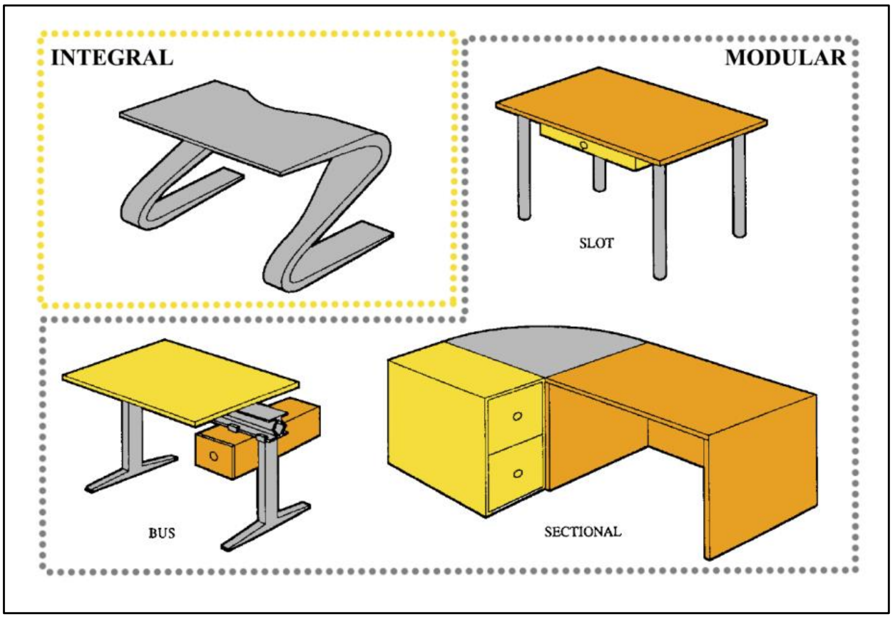


Figure 3.3. Integral & Modular architecture (Adapted from Ulrich (1995))

There are limited studies that evaluate the building system and decomposition approaches by considering the different physical and functional parameters, as buildings are more complex structures when compared to products. Understanding the utilization of product architecture, chunk development, modular architecture, transformation operators, and organization methods could enhance how to approach the system structure of the buildings. It can also create insights to develop the building structure organization using physical and functional aspects. The following sections particularly focus on the building system and the decomposition approaches at both system and component scales.

3.3.2 Decomposition of a building: System scale

The deconstruction of the building with several classification approaches has been addressed many times in different ways in the past. While Vitruvius evaluated architecture with six principles: order, arrangement, eurhythmy, symmetry, propriety, and economy (Vitruvius, 1999), Alberti approached the architecture by defining the six terms as locality, area, compartition, wall, roof, and openings

(Alberti, 1988). Over time, such decompositional thinking has been developed based on their subjects such as physical, semantical, and social parameters. Schmidt III & Austin (2016) classified the building decomposition approaches as levels, layers, and systems design to enable a better understanding of the building. While levels inform about the architectural strands related to decomposition approaches, layers include the explanation regarding the physical decomposition approaches. Systems design aims to divide the buildings considering the subsystems that it includes. The following two sub-sections elaborate on the division approaches in buildings based on the classification of Schmidt III & Austin (2016).

3.3.2.1 Levels

John Habraken defined the building as an ongoing process rather than an end product or a finished object (Habraken, 1972). Building upon this concept, he formulated the theory of levels, which hinges on the varying rates of change across different levels within a system. Accordingly, the dominance of levels that have longer durability (the slow cycling levels) over the levels that have shorter durability (the fast cycling levels) defines the system dynamics (Durmisevic, 2006). Within this theory, John Habraken introduced the concept of `Support and Infill (SI)` in the early 1960s. As a reaction to the housing boom in the Netherlands in the 60s, he proposed to authorize the user during the building process. To him, people deserve a more significant role in the decision-making process of building, aligning this approach to architectural terms support and infill (van Hoogstraten, 2011). In this approach, architecture should comply with the user's needs by providing them with a variety of choices for future changes in the everyday built environment (Schmidt III & Austin, 2016). The support and infill concept divides the built environment into three levels of decision-making: urban fabric, base building, and support and infill (Durmisevic, 2006). While urban fabric depends on the decisions related to the city, support and infill deal with the building. According to Habraken, governments are responsible for providing support structures that users can infill (Leupen, 2005b). While supports provide long-term use and include public service-related design decisions with heavy construction components, infill provides solutions for short-term use, and includes user-related design considerations with lightweight components (Kendall (2009), as cited in Schmidt III & Austin (2016)). The schematic diagram of his approach is illustrated in Figure 3.4.

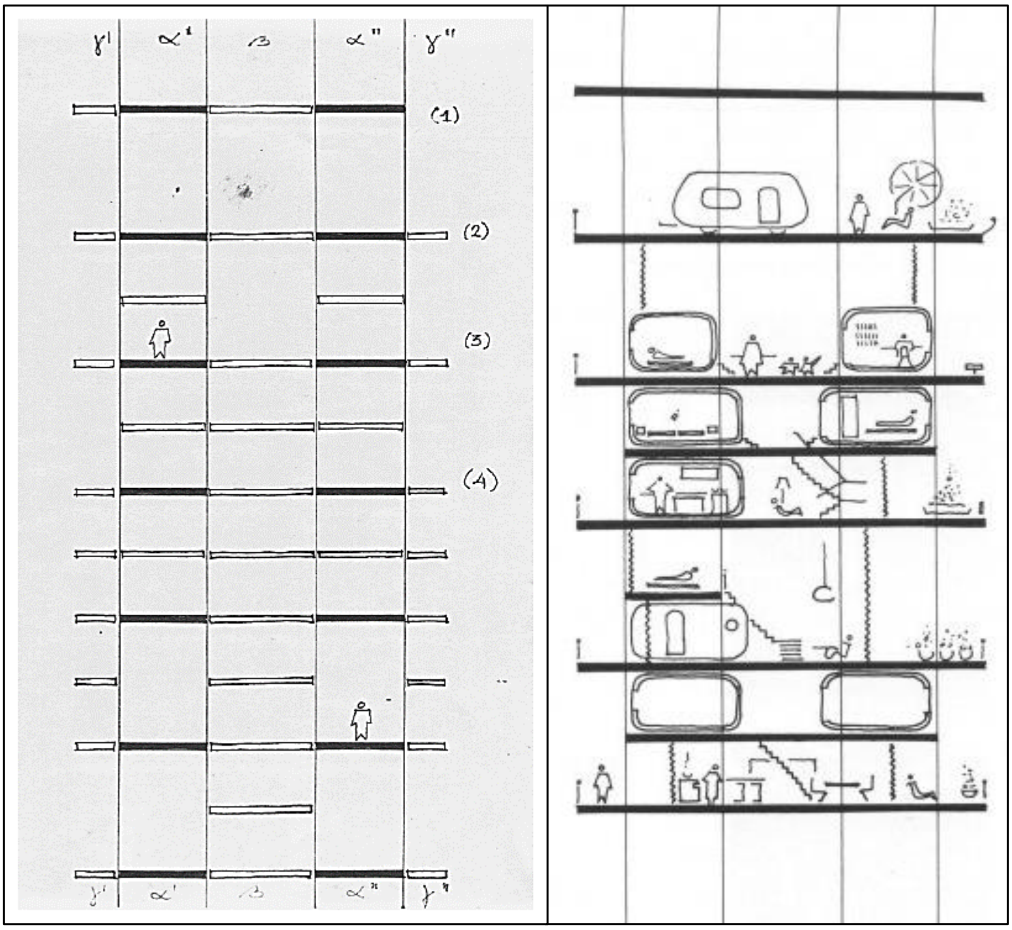


Figure 3.4. Habraken`s schematic representations for support (left) and for support and infill (right) (Habraken (1963) as cited in van Hoogstraten (2011))

CIB workgroup CIB104, an international network of researchers and practitioners, introduced an Open Building approach after the influential effect of the SI concept. Open Building aims to develop strategies for buildings and cities considering the fact that they should adjust, change, and transform towards the changing requirements.

The Open Building approach acknowledges that contemporary built environments encompass both stability and change simultaneously (Kendall, 2006). It uses environmental levels, which define the interrelated configurations of physical elements and decision clusters, to organize the process of designing and building in the built environment (Kendall, 2006) (Figure 3.5). Open Building is an umbrella term that includes ideas such as representing the built environment as support (or base building) and infill (or fit-out), enabling participatory design with users and other professionals, providing interchangeable systems in a base building, and recognizing the change and transformation as constant factors of building environment (Kendall, 2015). It embraces the concept of design for change and its principles and leads the development of strategies for building adaptability (Heidrich, Kamara, Maltese, Re Cecconi, & Dejaco, 2017). It improves the level separation by embracing the industrialization of construction and other approaches such as design for manufacture, disassembly, and reuse (Schmidt III & Austin, 2016).

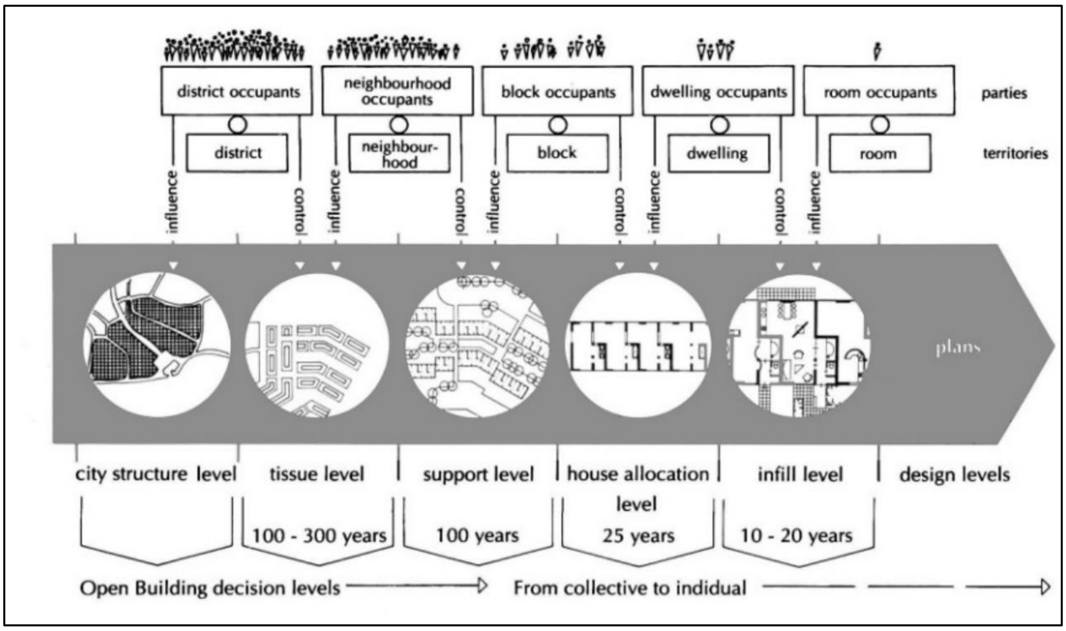


Figure 3.5. The principle of environmental levels (Habraken, 1963)

As Dutch evolutionary movements, Support&Infill and the Open Building emerged to address the challenges of the housing boom, the Japanese government also responded by implementing construction rules, tax incentives, and various technical innovations to improve the building stock by the late 60s. This action was prompted by the inadequate existing building stock, characterized by poor quality and short lifespans, which struggled to meet the growing demand (Minami, 2017). The Century Housing System (CHS) was proposed during that period to extend the building's longevity by using a systems approach. It emphasized the changeability of components over the lifespan of the building, aiming to decrease premature functional obsolescence by increasing the building`s adaptability (Schmidt III et al., 2010). The fundamental principle of CHS is to sequence the assembly of components so that those with shorter service life are installed after those with longer service life. (Kendall, 1999). By designing the buildings with such a philosophy, components with long service life are not damaged when components with short service life are replaced (Minami, 2017; Schmidt III & Austin, 2016). Mutual interfaces between components were carefully studied and required details were developed to ensure the service life compatibility between the components (Minami, 2017). As a result, buildings are categorized into component groups based on their respective service lives. While the building itself may have a long lifespan, its components were grouped according to durations such as 4,8,15,30, and 60 years (Stephen Kendall, 1999; Schmidt III & Austin, 2016). Service lives established for each component were as follows: 3-6 years for consumables, 6-12 years for items, 12-25 years for kitchens and washstands, 25-50 years for interior walls, ceilings, and floors, and 50-100 years for structural frames (Minami, 2017). Table 3.2 summarizes the component categories based on CHS principles.

As a derivative of the Support and Infill concept of Habraken (1963), the Skeleton and Infill system originated in Japan after CHS. In this system, a building is segmented into two parts in accordance with their different functions and the service life of the components. Connections between these two parts are established during the construction delivery process (Cao, Li, Yan, & Yuan, 2018). The skeleton part, as a fixed system, includes the primary structure and public access whilst the infill part, which provides flexibility and variability to satisfy the changing demands, contains the internal walls, indoor pipelines, flooring, and integrated kitchen/bathroom (Cao, Li, & Liu, 2015).

Table 3.2. CHS`s component categories
(Developed with reference to Minami (2017) and Schmidt III & Austin (2016))

Component examples	**Lifespan category**	**Average**
light bulbs, packing	3-6	4
hot water heater, home appliances, piping, wiring	6-12	8
moveable partitions, built-in furniture kitchens, washstands	12-25	15
exterior door and windows, roof interior walls, ceilings, floors	25-50	30
Foundation, main columns, beams	50-100	60

Within this context, NEXT21 was designed and built as an experimental multi-family house project, anticipating a 21st-century and highly individualized lifestyle of new century in a high-density energy-conscious building (Minami, 2017). Two principal concepts were integrated into the design: the systems building and the two-stage building. Systems building includes multiple independent subsystems that enable the building to become a flexible and adaptable structure, capable of accommodating changing requirements such as technological advancements, evolving individual lifestyles, and shifting occupancy patterns. On the other hand, the two-stage building provides the infrastructure and the infill. The infrastructure serves permanent areas for the community while the infill provides flexible personal property for the individual owners (Kim, Brouwer, & Kearney, 1993). The skeleton was designed by a single architect, and the units were designed by 13 different architects. The structural system, serving as the sole fixed component of the building, provides great flexibility to accommodate different lifestyles, and other parts of the building include a series of independent components (Minami, 2017). The building frame or skeleton, the exterior cladding, the interior finishes, and the mechanical systems were regarded as independent building subsystems. Each subsystem was viewed as having a different life cycle, requiring replacement or repair at different times (Stephen Kendall, 1999) (Figure 3.6).

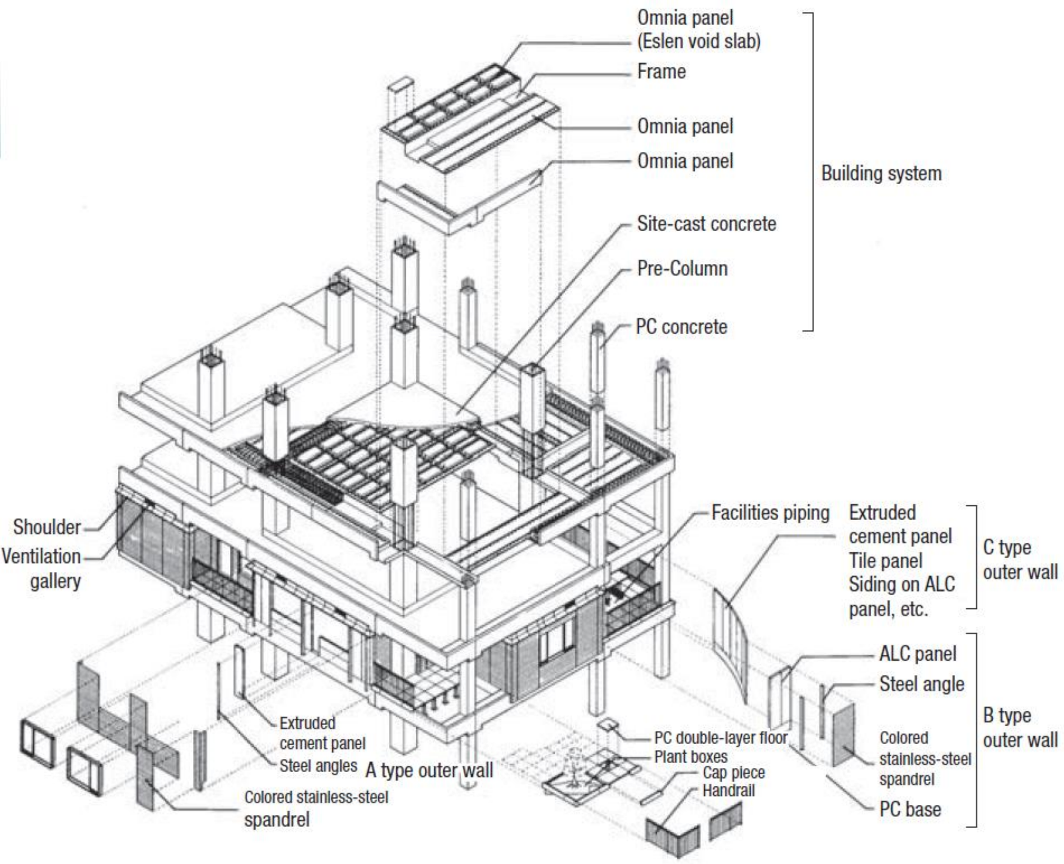


Figure 3.6. Independent building systems of NEXT-21 project (Osaka Gas Co. Ltd., 2007)

3.3.2.2 Layers

Systems thinking has significantly influenced our perspective on transforming the building industry. The push to industrialize the building sector has led to the assessment of buildings as a collection of systems or subsystems. This anatomical approach, which originated from human biology, focuses on how the parts were designed and how effectively they acted together (Arnold, 1987). Since then, many attempts have been made to analyze buildings and their components with such approaches. Following Habraken`s level theory, Rush (1986) developed the Building Systems Integration (BSI) theory, which categorizes building systems into Structure, Envelope, Mechanical, and Interior. These systems are interconnected with different levels of integration, and designers can explore alternative levels of integration to generate solutions for space, material, and time conservation. He employed bubble-type diagrams to illustrate building components (such as roofing, ceiling, and lighting) as elements within the four systems and demonstrate their interconnections and relations. He evaluated building components` dependencies with the physical relations as remote (do not physically touch), touching (contact, but not permanent), connected (permanently attached), meshed (located in the same space, limited compared to connected), and unified (whole).

The layers concept lies in the idea that building elements with different lifespans should be constructed distinctly. Frank Duffy, who proposed the first theory of the rate of change in buildings, evaluated the time factor in buildings and advocated that buildings should be evaluated with time, not with material entities (Schmidt III & Austin, 2016). According to him, “buildings aren`t made out glass, concrete, and stone: they`re made out of time, layers of time” (Genevro, 2009). As Steward Brand quotes Duffy: "Our basic argument is that there isn't such a thing as a building…A building properly conceived is several layers of longevity of built components" (Brand, 1994, p.12). Based on these ideas, he proposed to measure the buildings in terms of time with four S`s: shell, service, scenery, and set (Duffy, 1990). Shell includes the permanent structure and enclosure of the building which lasts 50-70 years; services consist of the heating, ventilation, and cable infrastructure of a building with a life span of 15 years or less; scenery refers to the fitting-out components to adapt the building shell for specific use with life spans 6-7 years; and set includes the arrangement of furniture and stuff for daily changes (McGregor & Then, 1999).

Stewart Brand developed this idea and proposed the theory of “Shearing Layers” in his pioneer book `How buildings learn: what happens after they`re built` in 1994. He expanded Duffy`s four S`s into six S`s. The idea of shearing layers aims to measure the building with the relations of building components and change needs at different rates (Brand, 1994). The layer model of Brand (1994) evaluates the time factor in buildings and decomposes buildings in terms of the life span of each layer. These layers were identified as site, structure, skin, services, space plan, and stuff, which last respectively, eternal, 30-200 years, 20 years, 7-15 years, 3-30 years, and 1 day-1 month. Site includes context-related information such as the geographical setting, and urban location; structure deals with the building components such as the foundations, and load-bearing elements; skin consists of exterior cladding components; services are the mechanical system components such as cables, plumbing, ventilation, elevators; space plan are related with the elements regarding walls, ceilings, floors; and stuff includes furniture, appliances, fixtures and daily used objects (Figure 3.7).

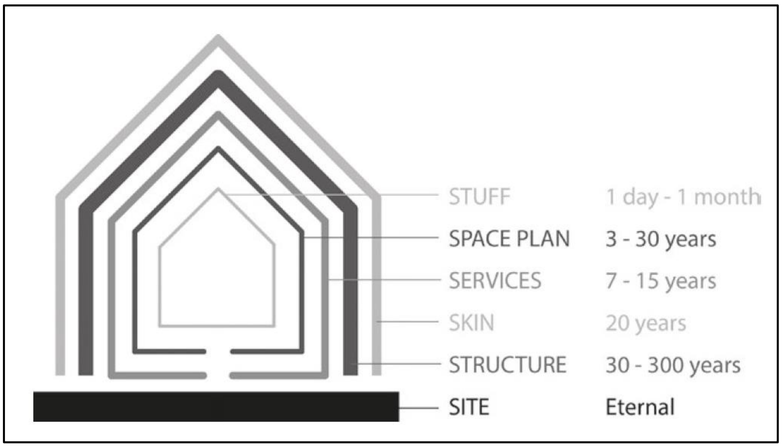


Figure 3.7. Shearing layers (Brand, 1994)

Primmler & Eppinger (1994) developed a methodology to analyze the relations in complex systems. The study is proposed considering a product architecture in a product; however, it can be applied to any kind of system. According to that, elements of a system can be evaluated with four types: *spatial,* defining the needs adjacency or orientation between two elements; *energy,* including the associations of energy exchange; *information,* identifying needs for information or signal exchange between two elements; and *material,* defining the needs for material exchange between two elements. Sosa, Eppinger, & Rowles (2000) studied the effects of technical interactions of design teams and provided a method to analyze their reflection on both the system and the structure of the organization. They classified the interactions in a system as: *spatial* for the physical adjacency for alignment, orientation, serviceability, assembly or weight; *structural* for transferring loads, or containment; *energy* for transferring heat, vibration, electric or noise; *material* for transferring airflow, oil, fuel or water; and *information* for transferring signals or controls.

Slaughter (2001) developed a systematic approach to analyze the characteristics of changes in the built environment and provided design strategies to increase adaptability. Their research presented the building decomposition as structure, exterior enclosure, services, and interior finish systems and divided the systems interactions of the building as physical, functional, and spatial. Physical interactions among systems manifest in forms such as connection, intersection, or adjacency. Functional interactions involve shared systems between functions, which may either complement or degrade the current function. For instance, a natural lighting system can enhance illumination alongside artificial lighting but could potentially disturb the performance of the heating system if a window is left open. Spatial interaction encompasses systems operating independently within the same room. For example, the interior lighting system may interact differently with interior surface finishes depending on various work settings.

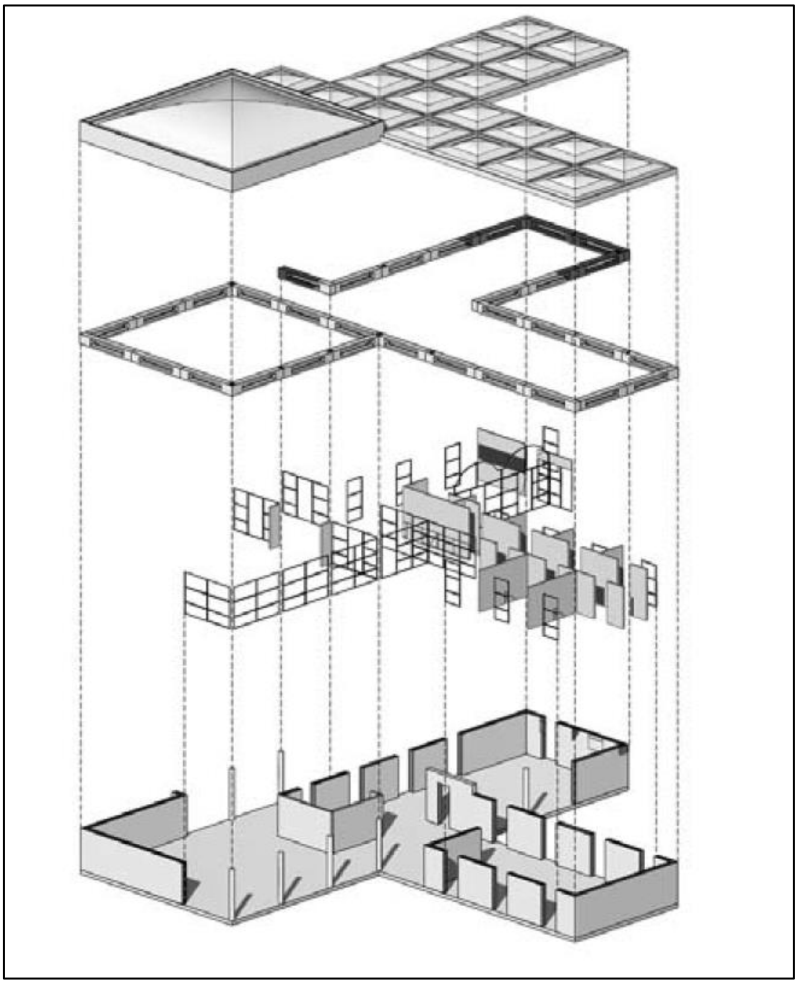


Figure 3.8. Decomposition of Van Eyck`s Orphanage with layer definition of Leupen (2005a)

Leupen (2005a) pointed out that buildings should be evaluated with permanent and changeable definitions and proposed the `Frame and Generic Space` idea. He defined the frame as a permanent and durable component, which forms the foundation for change within a building. This frame constitutes the space for change, referred to as generic space. With that aim, he proposed to evaluate the buildings with five layers: main loadbearing structure (columns, beams, loadbearing walls, structural floors), skin (façade, base, and roof), scenery (cladding, internal doors, and walls, finishing), service elements (pipes, cables, appliances) and access (stairs, corridors, lifts, galleries). Components in the main loadbearing structure transmit the loads to the ground; skin separates inside and outside; scenery describes the space with its visual and tactile elements; service includes the elements to regulate the supply and discharge of water, energy, and air with necessary appliances; and access ensures the availability and ease of access to spaces. He studied several cases with frame and generic space ideas and showed how buildings decompose according to this approach, as shown in Figure 3.8. Since the concept of Frame and Generic Space was developed in the PhD thesis by Leupen (2002), it serves as a reference point for the timeline of building decomposition studies.

Bachman (2003a) discussed the integration of building systems and their effect on architectural thinking. With the advent of the industrial age, buildings have come to encompass numerous systems, leading to a shift from passive methodologies to intelligent robotic servicing. In order to comprehend the nature of these systems and analyze them effectively, Bachman advocated for systematic thinking in the building design process and proposed the classification of building systems. To him, building systems can be evaluated as envelope, structural, services, interior, and site. *Envelope* is used for the separation of indoor and outdoor conditions; *structural* is used to understand the static behavior of elements against gravity and dynamic loads; *services* include the elements of HVAC, electrical, plumbing, vertical transportation, and life safety systems; *interior* defines the occupied space with partitions, finishes, lighting, acoustics, and furniture; and *site* includes the landscape and support systems as parking, drainage, vegetation, and utilities. Bachman also delineated three distinct types of integration in buildings:

- *Physical Integration*: This involves defining the systems that share a common area or volume in a space. An air-conditioning duct passing through a steel bar joist system is an example of physical interaction.
- *Visual Integration*: It is employed to express a system or a combination of systems creating a coherent whole. Compositional techniques that are used in visual integration consist of modifications of the color, size, shape, and placement of systems and their component pieces. Hidden structural and mechanical systems can be an example of visual integration.

- *Performance Integration*: This type of integration concerns relations regarding the individual components or elements serving multiple functions. For instance, a wall can be used to divide the spaces and to carry the window frame to get light.

Zimmann, O`Brien, Hargrave, & Morrell (2016) from the ARUP Group explored the circular economy principles and their application to the built environment. Their report presented multiple approaches, identified the challenges, and showed opportunities for circularity in the built environment. They also evaluated the layer model of Brand (1994) and expanded its layer definition with the layer `system`. They used a layer model to define circular strategies specifically for each layer in order to provide repair, replacement, and adaptation throughout the lifespan of the building. Accordingly, the system layer includes the structures and services enabling the overall functioning of the system such as roads, electricity and water systems, parks, schools, and digital infrastructure.

Schmidt III & Austin (2016) also worked on the layer model of Brand (1994). Their aim was to evaluate the dependency between building layers and they proposed design solutions to increase the adaptability of system architecture in the selected cases. They added two layers of the Brand`s shearing layers: social and surroundings. The social layer pertains to the humans within and around buildings who contribute to the life and dynamics of the building. Surroundings encompass the larger physical context of the building such as neighboring buildings and public space. Other layers have similar definitions to those of the Brand (1994). *Site* involves the legal boundary of the building; *structure* has the components for transferring the vertical loads and horizontal bracing; *services* encompass the components related to energy and water supply, communication transfers, and elevators; *space plan* includes the components that enclose the spaces such as partition walls, flooring; *skin* consists of the components related with the exterior façade; and *stuff* contains furniture systems. In order to understand the dependency between the building layers, they have proposed three types of flows considering the building terminology and context: *structural* to evaluate gravitational and lateral loads, *spatial* to understand the adjacency between components and circulation, and *service* to analyze the energy and water flows.

The study of Friedman (2001) used hierarchical characterization to increase the understanding of the workings of a system. He pointed out that a hierarchical structure can provide an order that allows mapping and ranking of the elements in a system. With this analytical methodology, he contributed to the understanding of incomprehensibly complex units such as a city or a suburb. He decomposed the suburban city into five divisions: district (quarter), neighborhood, cluster, group of units, and dwelling unit. All of the referred studies utilize an anatomical approach to distinguish the selected systems, whether they pertain to buildings, cities, or any type of system. This approach aims to enhance understanding of these systems by achieving several objectives. Building decomposition approaches and semantic relationships were mapped in the timeline presented in Figure 3.9. A detailed list of literature review of decomposition approaches with the categorization of the aims was also provided in Appendix A. The subsequent section further elaborates on an important methodology that outlines how to analyze the relationships and dependencies between components based on various parameters.

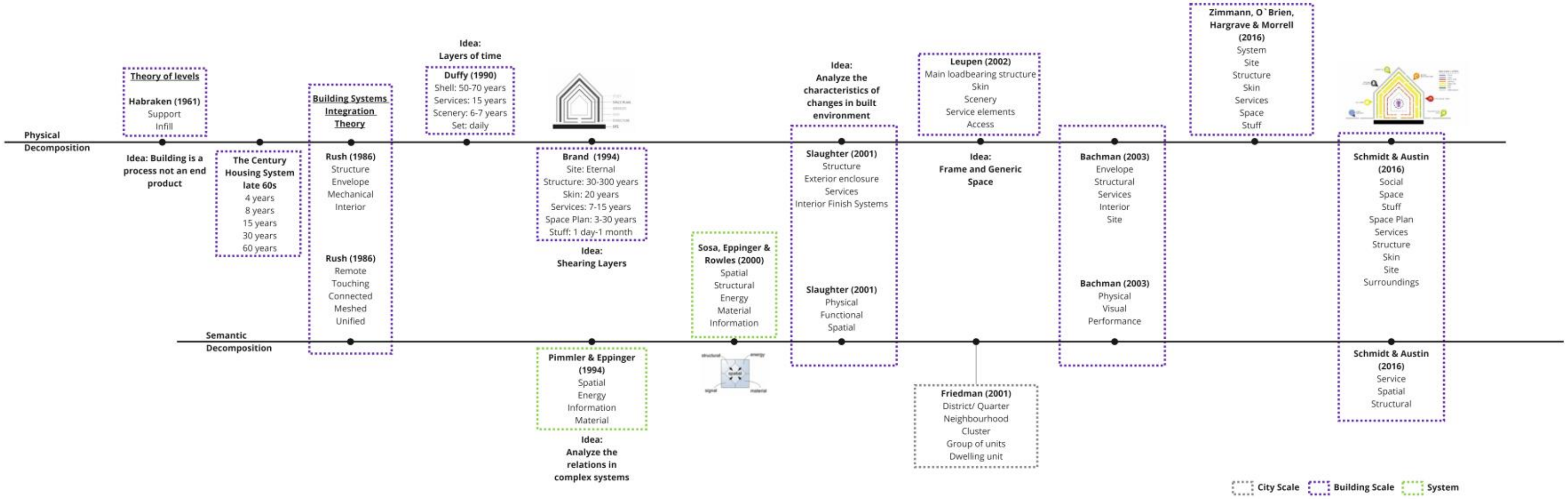


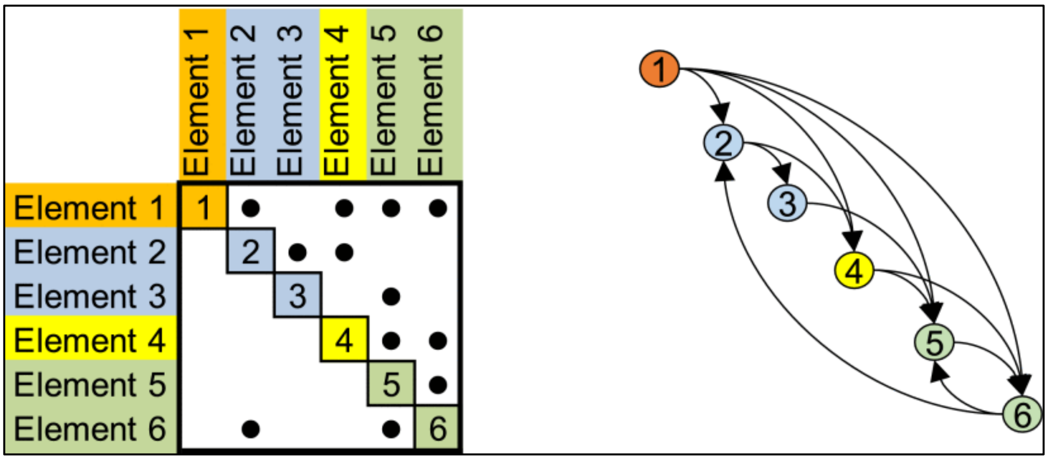
Figure 3.9. Timeline of building decomposition approaches

3.3.2.3 Design Structure Matrix

In the current milieu, complex systems like products, processes, organizations, cities, and living organisms involve the people. The classical approach to evaluate such complex systems is to model them through:

- Decomposition into the subsystems that we are relatively more familiar with
- Presentation of the relationships between the subsystems to understand the system behavior
- Evaluation of the external inputs and outputs and their impact on the system (T. R. Browning, 2001).

In the domain of systems engineering and project management, the Design Structure Matrix (DSM) emerges as an analytical method for evaluating dependencies and relationships among various components or tasks in a complex system. Eppinger and Browning (2012) defined it as: “Design Structure Matrix is a network modeling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system`s architecture” (p.2). It is a square NxN cell matrix that assesses the relationships between the elements or components within a single medium, as demonstrated in Figure 3.10.



	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6
Element 1	1	●		●	●	●
Element 2		2	●	●		
Element 3			3		●	
Element 4				4	●	●
Element 5					5	●
Element 6		●			●	6

Figure 3.10. DSM matrix and its equivalent node-link diagram (Tyson R. Browning, 2016)

DSM is used to illustrate the dependency state of a system, each pair being categorized as independent (blank cell), dependent (X depends upon Y), or interdependent (X depends on Y and Y depends upon X) (Schmidt III & Austin, 2016). Diagonal cells express the system elements (components in a product, people in an organization, or activities in a process) while off-diagonal cells represent the relationships (dependencies, interfaces, interactions) among the elements (Tyson R. Browning, 2016).

DSMs can be classified as static DSM (of a product or an organization) and time-based (of an activity). Static DSMs include the system elements that exist at the same time (Browning, 2001). Static DSMs are analyzed by clustering which is conducted with the rearrangement of the elements into chunks or modules (Schmidt III & Austin, 2016) (Figure 3.11). Static DSMs are component-based or architecture DSM and team-based or organization DSM:

- *Component-based or architecture DSM:* this type includes the system architectures depending on components or subsystems and their dependencies.

- *Team-based or organization DSM:* it is useful for analyzing the organization structures based on people or groups and their interactions. Time-based DSMs have an ordering in rows and columns that indicate a flow through time such as activities in a process. They are analyzed using sequencing algorithms. Time-based DSMs are activity-based or schedule DSM and parameter-based or low-level schedule DSM:

- *Activity-based or schedule DSM:* it is utilized for presenting processes and activity networks based on activities and the flow of information.

- *Parameter-based (or low-level schedule) DSM:* it is used to evaluate a design process at the level of parameter relations (Browning, 2001).

Through the application of Design Structure Matrix, it becomes possible to make advancements to a system without significantly altering its elements or their interrelations. Modifying the way of structuring elements can enable substantial benefits such as grouping product components into different sets of modules, organizing people into alternative teams, or adjusting activity sequences in a process (Eppinger & Browning, 2012). To analyze the relations effectively, it is important to define dependencies between components. While most DSMs are binary (either a dependency exists or doesn`t), numerical values, colors, and other symbols can be used to evaluate attributes, strengths, or the type of interactions (Schmidt III & Austin, 2016). The selection of parameters depends on the researcher's objectives and is tailored to the specific product or case under investigation.

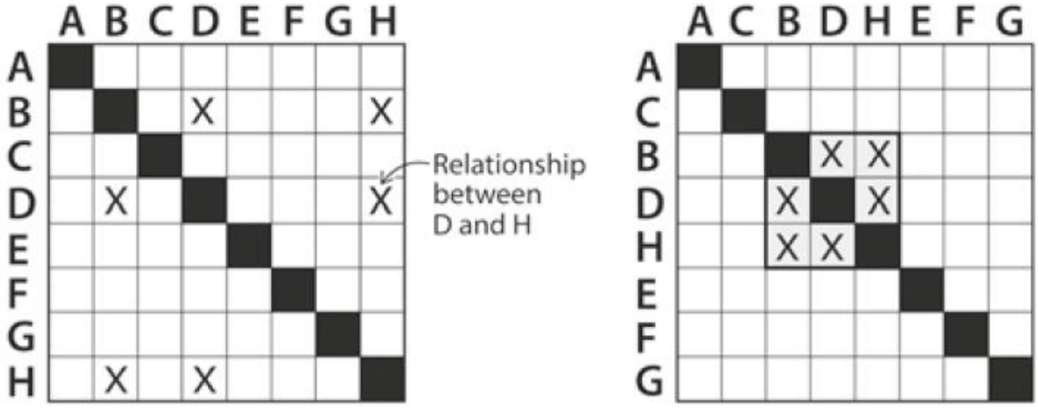


Figure 3.11. Clustering method in DSM (Schmidt III & Austin, 2016)

For instance, researchers may evaluate component relations based on spatial, energy, information, and material interactions, as demonstrated in the case of the Ford Car Climate System. The study revealed three important clusters: interior air, refrigerant, and front-end air, as illustrated in Figure 3.12. These clusters encompass interactions of materials, energy, and spatial types. However, in the controls/connections chunk, the interactions were primarily spatial and informational. From this perspective, it can be inferred that certain types of interactions may be clustered as product modules, while others are dispersed throughout the entire system. It is crucial to note that the automobile`s engine was not integrated into the study, leading to some interactions being analyzed with a lack of heating loop and altering the overall results. Therefore, defining system boundaries is essential before employing DSM methodologies (Eppinger & Browning, 2012; Pimmler & Eppinger, 1994b).

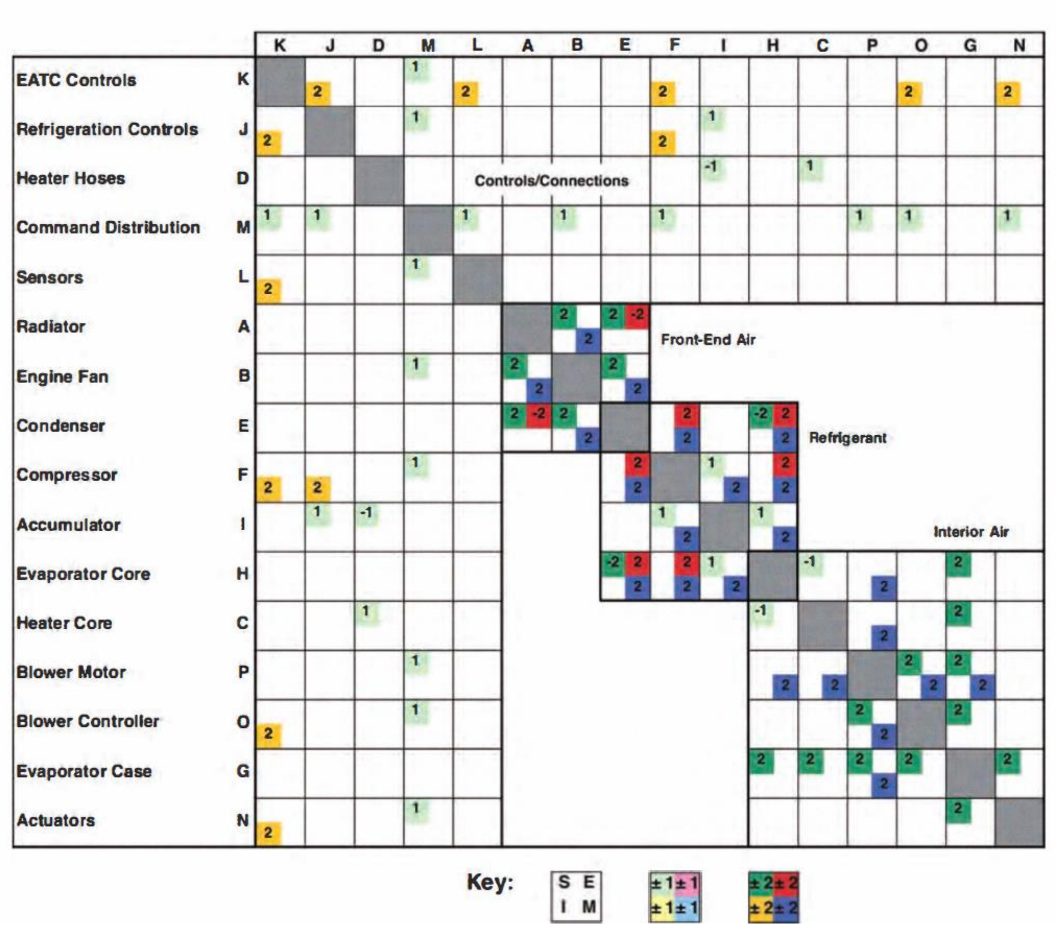


Figure 3.12. DSM of Ford car climate system with clusters and a chunk (Eppinger & Browning, 2012)

In the context of complex systems in the built environment, several studies have applied DSM methodology to evaluate system architecture. One such study by Björnfot & Stehn (2007) focused on evaluating long-span timber structures to identify constructability barriers between structural design and assembly and to decrease waste generation. Force transfer and geometric constraints were defined as interaction types between the elements. DSM for the geometric constraints was found symmetric in the results, indicating that changing an element in one part will affect the symmetric part. The roof system emerged as the primary subsystem among other subsystems, suggesting that the roof should be prioritized in the assembly to ease the constructability.

Geyer (2009) conducted a study on an optimization model, which considers the uniqueness of the building, within a case study of a multipurpose hall. They employed DSM and a multi-objective genetic algorithm as the methodology. DSM facilitated defining the relationships between components and proposing system modifications and alternative designs represented by a circuit diagram. For example, the façade can be supported with a layer of beams or span directly from one frame to another depending on the span distance.

Another study focused on investigating whether schools can accommodate the changing demands of the users. The researchers utilized DSM to capture designer decisions and uncover hidden design dependencies in the selected educational facility. The dependencies between building components were categorized as structural, spatial, and services. In the results, two modules were constructed between the layers: one compromising structure, and another including skin, services, space plan, and space. Strong connections were observed between the structure and space layers, while less dense modules showed movement outside their layers, and occasionally formed chunks within their layers. It is also found that there can be some combinations between components and layers, such as the structural layer with some components in the services and skin layers. The study provided further insights into identifying components that need further design for alternative layers and recommending changes at the component level (Eppinger & Browning, 2012; Schmidt III, Austin, & Brown, 2009).

After reviewing the selected cases, it was interpreted that the primary aim has a key role in utilizing DSM to define the system and its boundaries. Additionally, the definition of dependency types between components is vital to explore the type of relation between components and should be tailored to the specific case under investigation. DSM can be employed to construct multiple diagrams including N^2 diagrams, breakdown structure diagrams, and matrices to analyze relations within the system. For a deeper understanding of DSM structures with various examples, revisiting the aforementioned articles as well as the influential book by Eppinger& Browning (2012) can be of great guidance.

3.3.3 Decomposition of a building: Component scale

In the design process of buildings, several considerations including functional, technical, and physical properties are evaluated. In the traditional approach, these considerations aim to reach the stage where the building is constructed. However, it is important for the design process to encompass considerations related to the operation phase of the building and to accommodate potential changes such as deterioration, obsolescence, repair, and refurbishment. As highlighted in previous sections, buildings are systematized and decomposed with several aims. The decomposition approach can also be applied to buildings on a component scale, enhancing the building's adaptability and changeability in response to such situations. To facilitate seamless changes in building systems, it is essential to evaluate building structures with a focus on decomposition approaches. By doing so, designers and stakeholders can better understand the interdependencies among building components and systems, enabling them to make informed decisions to enhance the building's longevity, functionality, and sustainability.

DECOMPOSITION ASPECTS		
Functional Decomposition	**Technical Decomposition**	**Physical Decomposition**
functional independence systematization	relational patterns type and position of relations base element specification	geometry of component edges assembly sequences connections life cycle coordination

Figure 3.13. Decomposition aspects (Adapted from Durmisevic (2006))

Durmisevic (2006) developed the decomposition aspects associated with building structures. Accordingly, there are three decomposition aspects; functional, technical, and physical, as demonstrated in Figure 3.13.

Functional decomposition evaluates the building components in terms of their functional distribution in a building. To ensure flexibility in building components, several strategies are used such as functional independence and systematization. While functional independence aims to distribute the shared functions to single components; systematization assesses the functional relations of the components and proposes component clusters for each function.

Technical decomposition focuses on decisions regarding the order within a configuration. When there is no clear hierarchy or order between components, the building structure becomes less adaptable to transformation. Apart from the functional relationships, analyzing components reveals relational patterns that inform about dependencies. The type and position of relations are important for increasing the transformability of the building. Base element specification is another method for technical decomposition, where a base element is defined to differentiate the clusters and combine components into independent assemblies. Moreover, it may serve as an intermediary with other clusters, enabling change without adversely affecting surrounding materials.

Physical decomposition encompasses the design properties of connections between components, which provide exchangeability and contribute to the potential for transformation. Physical decomposition can be categorized into various aspects, such as the geometry of component edges, assembly sequences, connections, and life cycle coordination. The types of physical decomposition are significant since they can be used to guide architects' decision-making processes at the component scale. The following body of text elaborates on these approaches, providing examples from the built environment to illustrate their application and effectiveness.

First, the geometry of component edges affects the assembly sequence of the building components. The interface design and specification of the connection type are the main determinant factors for the definition of product assembly relations. Figure 3.14 shows six conditions of component edges classified from open to interpenetrating geometry. Considering the generated damage of the surrounding components in case of a need for change, open geometries are better and preferable. The diagram of Durmisevic (2006) is further elaborated with a scale integration to give a measure for geometry selection in the decision-making process.

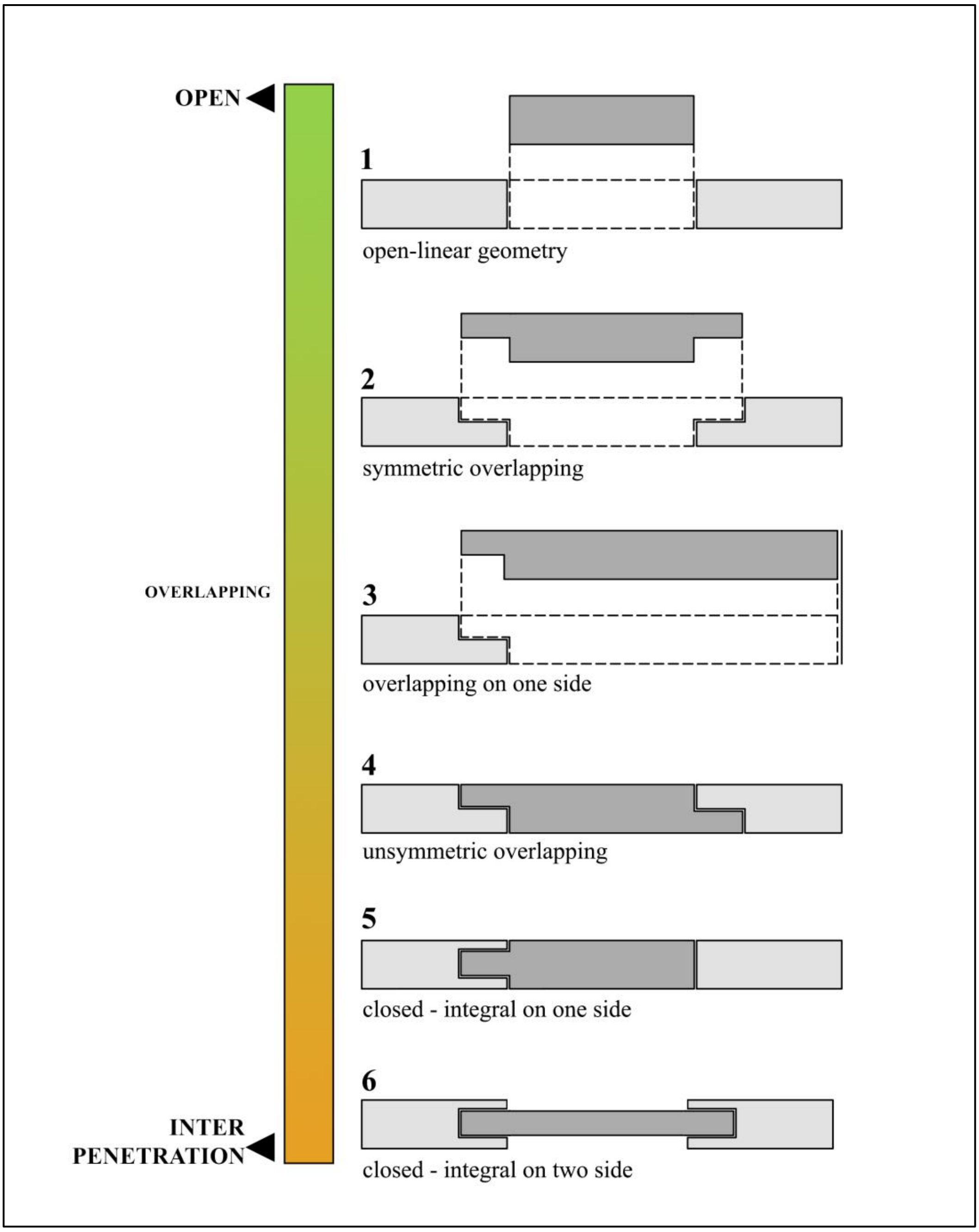


Figure 3.14. Geometry of component edges
(developed with reference to Durmisevic (2006))

Assembly sequences show the breakdown of the hierarchical relationships in buildings. It depends on the life cycle of assembled materials, type of materials, geometry of component edges, and type of connections. There are two main assembly sequences; parallel and sequential. Parallel assembly sequence can accelerate the construction process while sequential assembly sequence establishes dependencies between assembled elements, complicating the process of substitution and replacement. In parallel assembly, the disassembly process is conducted based on the type of connections between components. Each element in sequential assembly is fixed by a newly assembly element, building the linear dependency between the components. Types of assembly sequences can be increased based on the various interpretations of parallel and sequential assembly sequences, namely interlock, closed circle, and gravity (Durmisevic & Brouwer, 2002a) (Figure 3.15).

The design of building connections defines how the elements are combined. The main types of connections can be classified as direct (integral), indirect (accessory), and filled (Durmisevic, 2006). Filled connections include chemical connections or welded connections between metal plates. These types of connections are not suitable for adaption to the changes during the operation phase. Indirect connections mostly consist of the loose accessory that links the components. They need to be evaluated with assembly sequences. They are preferable to filled connections since they give less harm to the components during the dismantling process. Direct connections include the relations of overlapping and interlocking between the materials. Their disassembly depends on the type of material used in the connection, assembly sequences, hierarchical position of the components, and their relations with other components. Figure 3.16 shows direct, indirect, and filled connections with their scales from fixed to flexible. Flexible structures tend to have an additional fixture without damaging the elements. Fixed structures include mostly chemical connections and interlocking relations within each other.

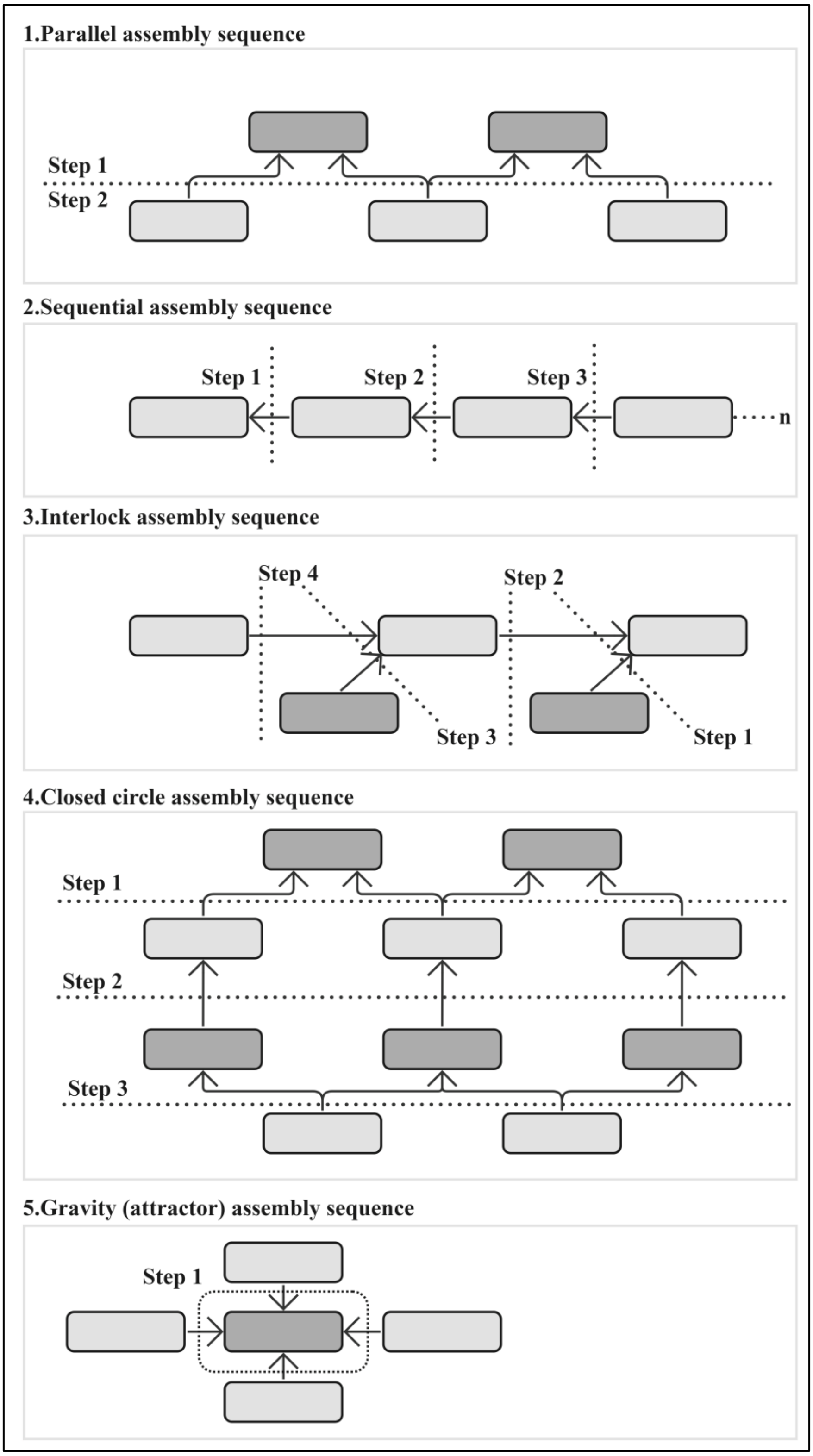


Figure 3.15. Assembly sequences (Adapted from Durmisevic & Brouwer (2002a))

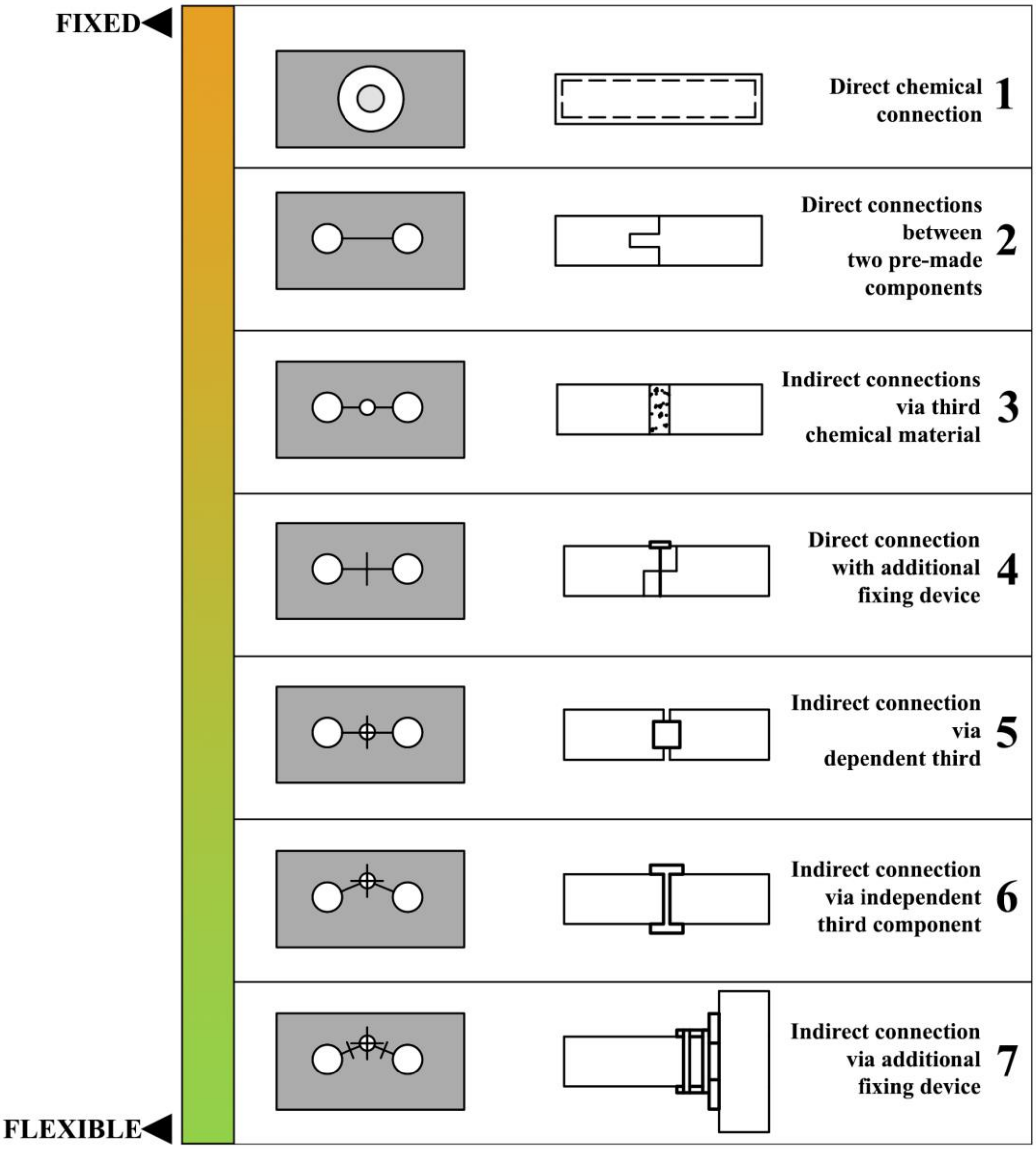


Figure 3.16. Connections with the scale (Adapted from Durmisevic (2006))

Life cycle coordination between the building components is necessary to control the assembly and disassembly sequences. Building materials have a wide range of lifespan from 5 to 75 years. However, building configurations are often not designed with respect to these lifespans. To that end, if elements that have a short life cycle are assembled first and disassembled last, the integrity of the whole structure may get damaged. In addition, the functional dependencies are determinants to evaluate the life cycle coordination between the components, as maintenance and repair needs change based on the function of the selected component. Accordingly, two life-cycle coordination aspects are important for achieving flexible structures: *(i)* assembly of materials that have varying life cycles, and *(ii)* assembly of materials that have functional dependencies (Durmisevic, 2006). In order to decrease the waste in material changes and decrease the energy loss, the life cycle coordination between components should be considered in the early design process.

3.4 Reflections of decomposition understanding to the digital tools

The aforementioned researches in the previous section primarily concentrate on illustrating the breakdown structure of the building from the system scale to the component scale. In this section, the focus is shifted to exploring various applications of decomposition understanding in digital tools.

Technological developments have continuously influenced the approach to information management in the construction industry. Up to the 1990s, several isolated tasks of information were being produced; however, the process of information management and transfer remained largely unchanged from thirty years prior. Given the complex interrelations within the construction industry, a disconnection between engineering, architectural design, and construction became inevitable. An analogy often used to describe this problem is `islands of automation`, highlighting the incompatibility among different fields within the construction industry (Björk, 1995) (Figure 3.17). Since then, numerous studies have been conducted to facilitate communication between the stakeholders in construction, aiming to provide a common ground for terminology and methods used in different phases of construction and to foster compatibility across different sources of information. This section elucidates the emergence of the product data model, delves into the classification systems, and culminates with an exploration of the Industry Foundation Classes, a commonly used data schema in the construction industry.

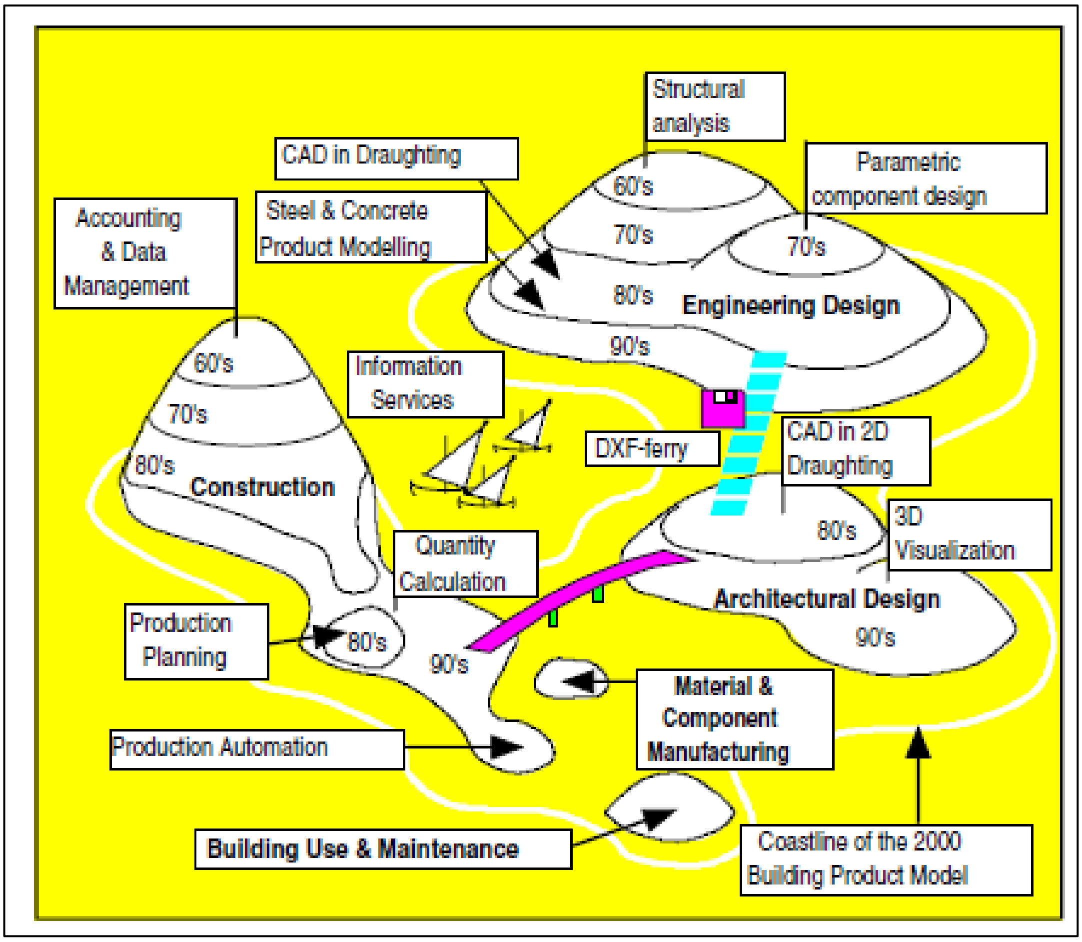


Figure 3.17. An analogy of `islands of automation` (Björk, 1995).

3.4.1 The emergence of the product data model

The proliferation of isolated tasks of information in the construction made information management increasingly challenging. To illustrate, a room might be described with the walls surrounding it in a 2D drawing software, while in another, it could be represented with a row showing the information about the room`s intended usage and area. On the other hand, an HVAC engineer might calculate the building`s total heat loss using inputs from the same room with the analysis program. This fragmentation led to the realization of the need for solutions that could provide a common ground for data sources and facilitate information sharing (Björk, 1995).

The RATAS project was initiated in 1986 and continued until mid–190s in Finland. It was a cooperation between industry and researchers concentrating on the shift from a document-oriented approach to a product model-oriented one for organizing the design information. The project aimed at providing transfer of data about buildings and their components in a database format. As an outcome, a conceptual data model was developed to establish the basic organization of data defining a building (Björk, 1994).

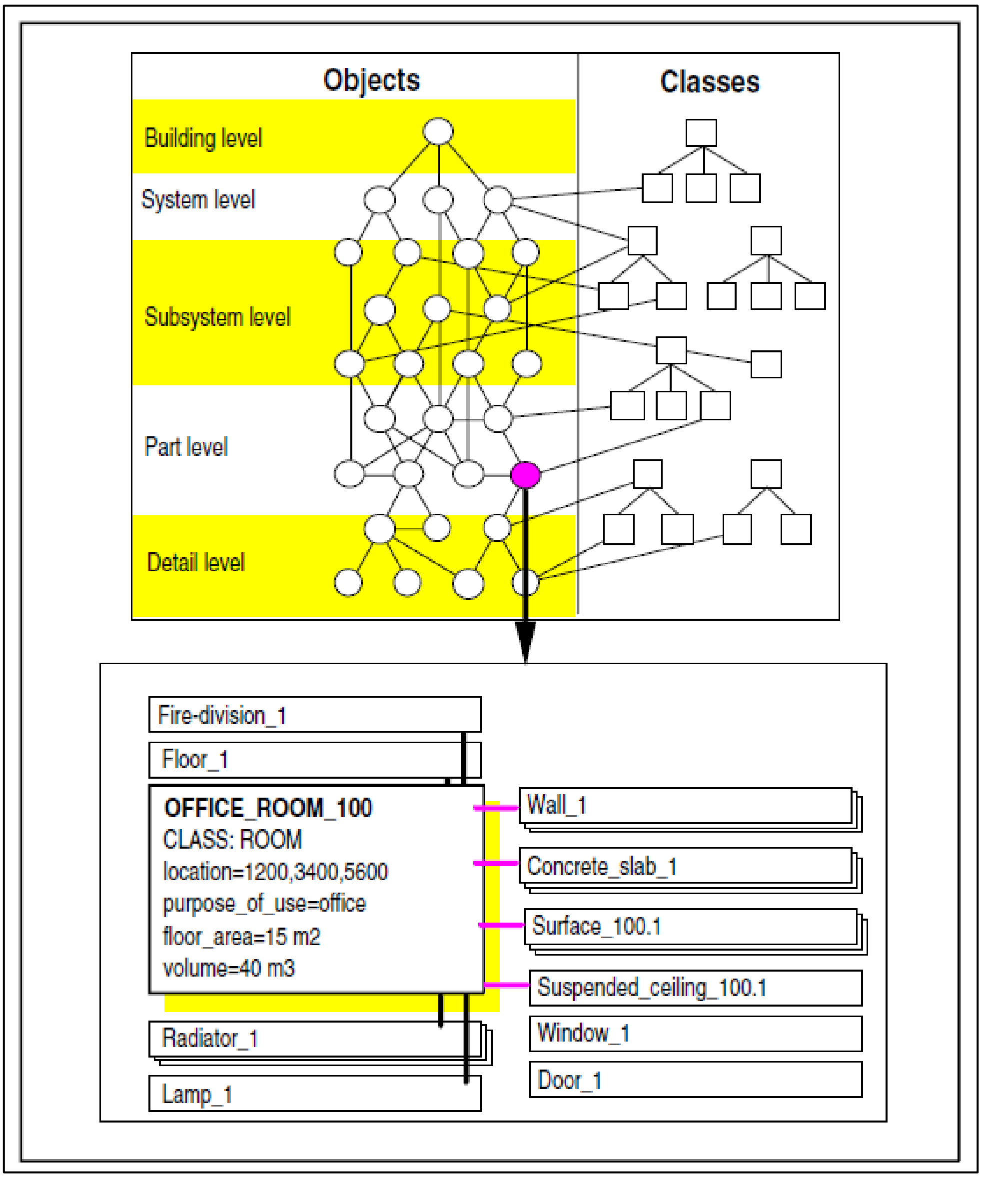


Figure 3.18. Component-oriented data model in RATAS project (Björk, 1995).

Accordingly, object classes include a fully detailed building product data model with five generic decomposition levels (building, system, subsystem, part, and detail). This hierarchical system has been proposed to understand the relations at each level between entities, as shown in Figure 3.18. On the topmost level, the model demonstrates the entity-relationship data model with a decomposition structure and generalization-specialization hierarchy. On the other hand, the lower portion involves the categorization of attributes and relationships between objects into various categories. Examples of attributes may include numbers, strings, and even raster graphics pictures (Björk, 1994, 1995).

3.4.2 Classification systems

Given the differences in data structures generated by various software applications, there arose a necessity to establish a common language for communication among different stakeholders in the construction industry. With the rise of information resources on the Internet and the World Wide Web, a system that has more organized information has become necessary to achieve efficiency in resource discovery (Saeed & Chaudhry, 2002). In response to these challenges, the construction sector has witnessed the development of many national and international standards and classification systems. These were designed to adapt to the rapid development and dissemination of information technology within the industry (Lou & Goulding, 2008).

3.4.2.1 Building classification systems

Building classification systems have predominantly been developed with consideration for the national and regional characteristics of construction and facility management processes. For the core ontologies common to the sector, there are two major international standards that later serve as a key reference for the development of other standards, namely ISO 12006-2 and ISO 12006-3 (Ekholm, 2005):

- *International Standards Organization ISO/DIS 12006-2:* a generic framework of classes in facility and construction management (ISO, 2005)
- *International Standards Organization ISO/DIS 12006-3:* the specification of a taxonomy model, which provides the ability to define concepts by means of properties (ISO, 2007)

Most of the standards and classification systems draw their main foundations from these standards. The classification systems based on the different regions and their contents can be exemplified as:

- *Uniclass (Uniclass 2015), United Kingdom:* a classification system for civil engineering works (National Building Specification, 2015)
- *Uniformat®, United States of America:* a classification for the description, analysis, and management of a building throughout its life cycle (Construction Specifications Institute, 2012)
- *MasterFormat®, United States of America:* a classification system for organizing construction bidding and contract requirements, specifications, drawing notes, and cost data. (Construction Specifications Institute, 2001)
- *OmniClass™, United States of America:* a classification structure for electronic databases and software (Construction Specifications Institute, 2006)
- *Stabu Lexicon, The Netherlands:* a multilingual tool for the management of construction terms, describing built objects and their association (Lou & Goulding, 2008)
- *Barbi, Norway:* a reference data library with a complete collection of concepts and objects from the building with their associated properties and relationships (Lou & Goulding, 2008)
- *BSAB, Sweden:* a classification for construction installation processes and considerations for computer applications (Lou & Goulding, 2008)

- *Industry Foundation Classes (IFC):* a modular structure for the development of model components, the ‘model schemata’ (Lou & Goulding, 2008)
- *buildingSMART Data Dictionary:* a data dictionary that is created for interoperability through standards. (BuildingSMART, n.d.)

Previous studies on classification systems have reviewed the field (Afsari & Eastman, 2016; Dikbas & Ercoskun, 2006; Kula & Ergen, 2018; Lou & Goulding, 2008), proposed new classification systems (Sibenik & Kovacic, 2019) and analyzed the improved version of the national classification system (Jørgensen, 2011).

3.4.2.2 Building data schema: Industry Foundation Classes

As indicated by the island of automation analogy (Figure 3.17), a standardized, common data exchange format was necessary to facilitate seamless building data transfer among the diverse software products utilized by stakeholders in the construction industry. In response to this need, the Industry Foundation Class (IFC) was developed. IFC incorporates both geometric and semantic information and provides a structured classification of building components, featuring a common hierarchy of types, detailed descriptions of relationships between components, and definitions of attributes (Borrmann, Beetz, Koch, & Liebich, 2018; Vanlande, Nicolle, & Cruz, 2008).

The IFC is an open international standard for data exchange among software applications (ISO, 2018). It was developed by buildingSMART to store data related to building components (Zhang & Issa, 2013). IFC schema was structured with four layers; domain, interoperability, core, and resource (Figure 3.19). The resource layer includes the definitions such as geometry, measurement, cost, date, and time whilst the core layer includes the kernel and extension modules that define abstract concepts for entity definitions. The core layer involves space, site, building, building elements, and annotations. The interoperability layer provides the sharable entities such as the beam, column, window, occupant, and flow segments. The domain layer involves entities such as footing, pile, plate, chiller, and boiler for different AEC domains in architecture, structural engineering, and mechanical engineering (Ramaji, 2016).

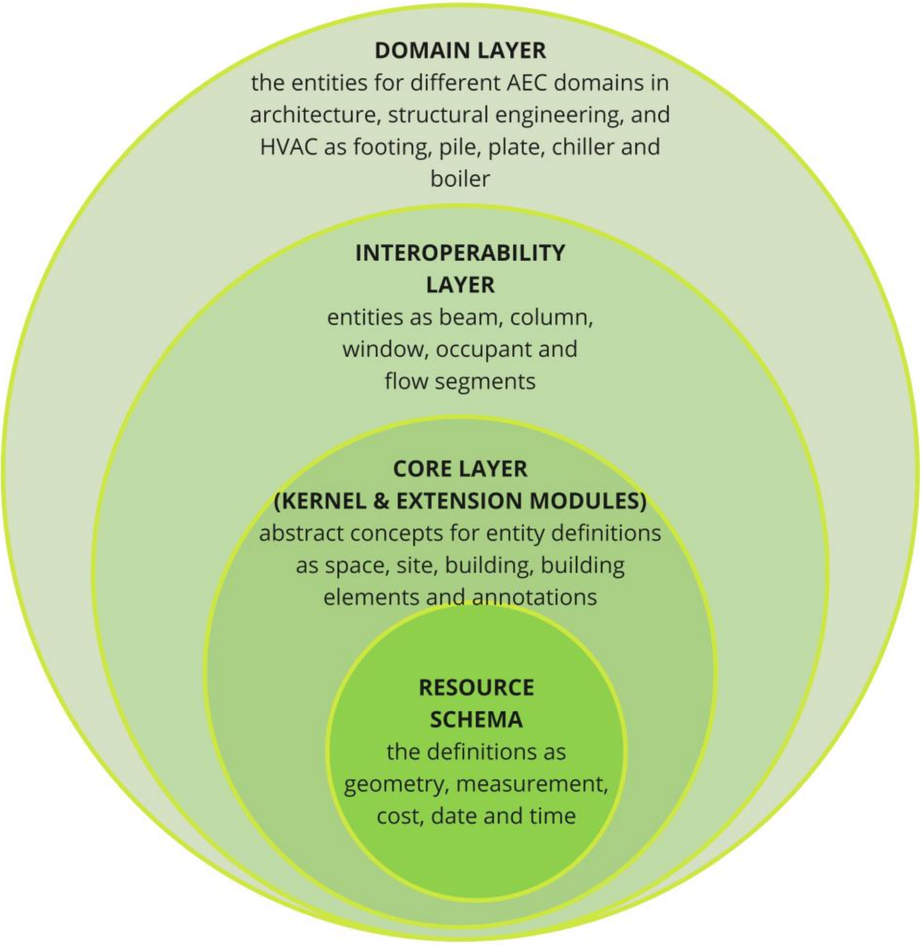


Figure 3.19. IFC data structure (developed by the author)

As in any object-oriented data model, inheritance hierarchy has an important role in IFC. It regulates the specialization and generalization relationships between the classes. From the core class *IfcRoot* to building elements such as *IfcWall*, *IfcColumn*, and *IfcWindow*, the hierarchical representation of different classes has been generated, as illustrated in Figure 3.20. (Borrmann et al., 2018). This unified information documentation creates an ease of data exchange between different stakeholders of the construction.

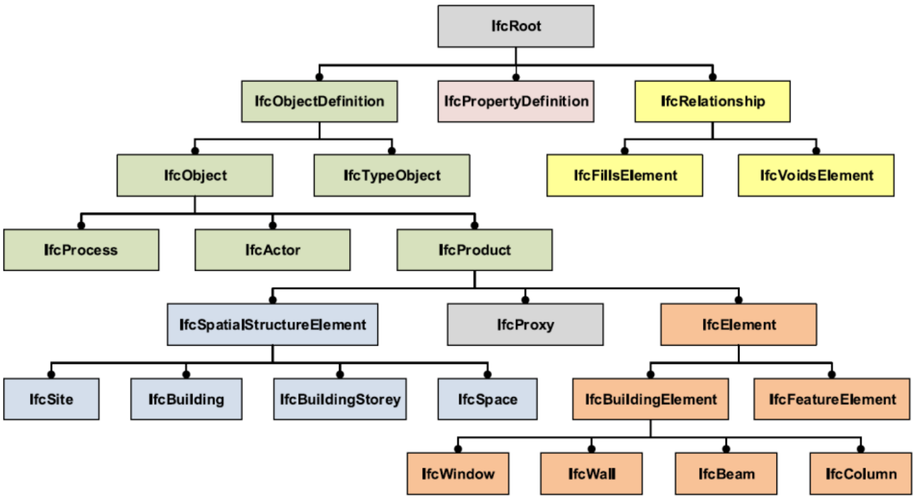


Figure 3.20. Partial IFC data model showing the inheritance hierarchy (Borrmann et al., 2018)

Since IFC is an interoperable data schema and enables data exchange, researchers have expanded their studies by adopting, transforming, or conforming to IFC definitions. In the literature, there are many studies adopting methodologies consistent with the IFC model. Among them, two studies are elaborated within the scope of this study. As previously referred, Geyer (2009) developed a method for multidimensional optimization for the building design process. In their study, quantitative and qualitative research methods were combined for the optimization of a multipurpose hall. The decomposition of building components was analyzed with DSM to understand the dependencies between components. The component scheme was expanded with the conformity of the IFC schema to allow a seamless integration into digital design tools in the future. This study provides valuable insights into the correlation between data information technologies and DSM methodologies, offering a holistic approach to building design optimization. On the other hand, Chen & Whyte (2021) proposed a new approach to predict design change propagation of engineering systems based on the use of Digital Twin and DSM. They used clustering analysis to decompose a building into more controllable modules for analyzing change propagation. The authors decomposed a tunnel in an infrastructure project with the help of IFC Schema in Digital Twin. This study presented an innovative perspective on exploring the relationships between DSM and Digital Twin approaches, offering new insights into the predictive capabilities of system design.

3.4.3 Current situation in digital tools

As information management is digitized, several software tools have been developed to cater to the needs of the architectural, engineering, and construction industries. Among these tools, Computer-aided design (CAD), Building Information Modeling (BIM), and Digital Twin (DT) stand out as successive technologies that play essential roles in the industry. Briefly, CAD allows users to create digital replicas of physical objects by design and visualization. It allows architects, engineers, and designers to generate detailed 2D and 3D models of structures, components, and systems. BIM, on the other hand, takes CAD to the next level by integrating additional layers of information, such as material descriptions, cost estimation, and scheduling into 3D models. It fosters collaboration and coordination among project stakeholders by providing a comprehensive digital representation of the building. DT builds upon BIM and extends its capabilities by providing a dynamic digital representation of a physical system or asset. It leverages real-time data from sensors, Internet of Things (IoT) devices and other sources to continuously update and synchronize the digital model with the physical environment. The following section delves deeper into BIM and DT concepts, highlighting their prominent properties and discussing how they can serve as valuable tools to support decision-making in the design process with the critical disposition.

3.4.3.1 Building information modeling

Building information modeling is an inclusive term that refers to a range of activities in object-oriented Computer-Aided Design. It involves the creation of digital representations of building elements, encompassing both their 3D geometric properties and non-geometric attributes and relationships (Ghaffarianhoseini et al., 2017). The development of 3D modeling, which formed the foundation for BIM, dates back to the 1970s and emerged from early computer-aided design efforts across various fields (Volk, Stengel, & Schultmann, 2014). Initially, designers and engineers utilized 2D design within CAD systems (Eastman, Teicholz, Sacks, & Liston, 2008). The concept of BIM was formally introduced by Jerry Laiserin in 2002. He presented BIM as a continuation of CAD systems, emphasizing the need for software that is interoperable and integrated (Laiserin, 2002).

The BIM concept was embraced by both academic and industry communities as the `new CAD paradigm` (Ibrahim, Krawczyk, & Schipporiet, 2004). Following this recognition, many studies emerged to refine the terminology associated with the concept. Eventually, the term "Building Information Modeling", as proposed by companies like Autodesk and Bentley, gained widespread acceptance (Succar, 2009). As interest in BIM grew, it was formally defined by the international ISO as "a shared digital representation of physical and functional characteristics of any built object […] which forms a reliable basis for decisions " (ISO, 2010; Volk et al., 2014). The concept of BIM can be defined both broadly and narrowly. In its narrow scope, it only involves the production of the building model in technical terms, while in its broad scope, it includes many sub-features, including functional, legal, organizational, and informative aspects (Volk et al., 2014). The application of BIM is presented with a framework that addresses all relevant BIM domains, stakeholders, and applicable project phases, as demonstrated in Figure 3.21. It is crucial to create an understanding of the current state of BIM applications as well as future BIM implementation requirements (Ding, Zhou, & Akinci, 2014).

With its capacity to get involved in various stages of project planning, major BIM architectural tools like Autodesk Revit, Bentley Architecture, Graphisoft ArchiCAD, and Gehry Technology's Digital Project have become widespread in the construction industry (Eastman et al., 2008). As cutting-edge technologies shape construction and architecture, BIM not only affects visualization methods of designs but also transforms the design process itself. Through BIM technology, architects and engineers have the ability "to add informational texture to designed objects (in terms of properties, materials, lifecycle, and other data) into the functional design" (Ghaffarianhoseini et al., 2017). Although the capabilities and applications of BIM expand as technology develops, its usage is predominantly observed in the following areas: design visualization, design assistance and constructability review, site planning, and site utilization, 4D scheduling and sequencing, 5D cost estimating, integration of subcontractor and supplier models, systems coordination, layout and fieldwork, prefabrication, and operations and maintenance (Campbell, 2007). Moreover, computable and 4D-based BIM applications are being developed, such as 4D quality management, 4D safety management, and 4D computational models for carbon emissions (Ding et al., 2014).

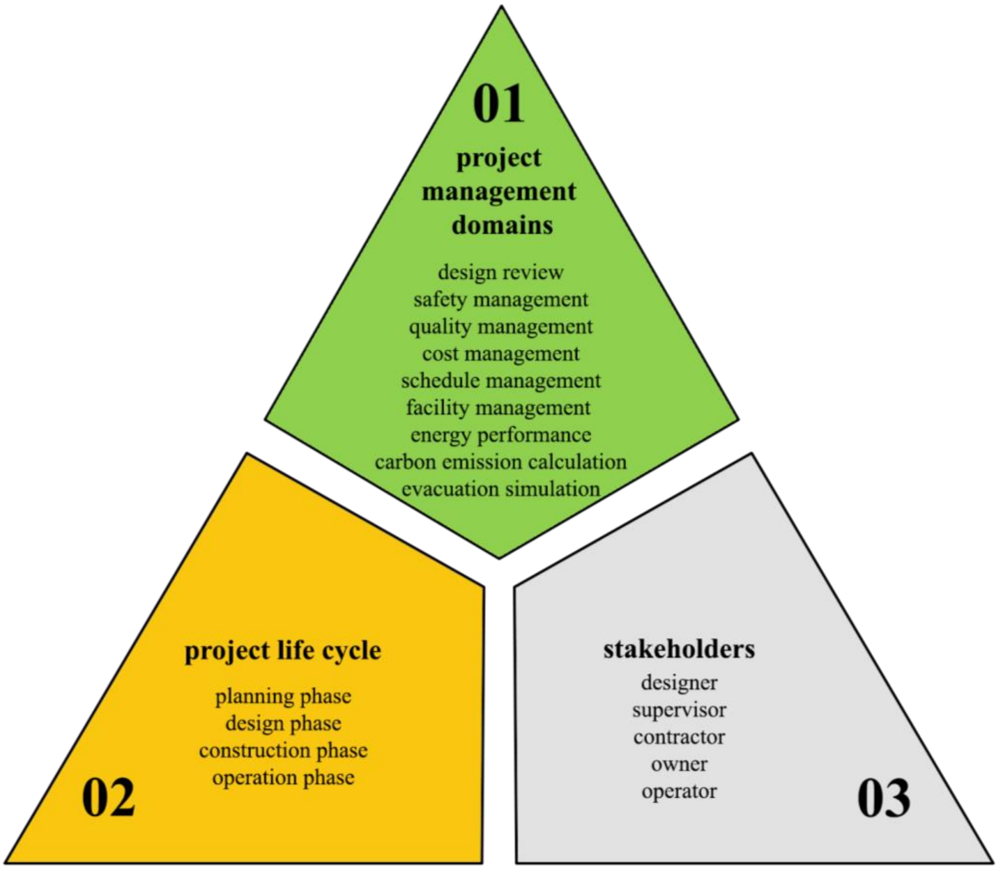


Figure 3.21. BIM application framework (Adapted from Ding et al. (2014))

Although BIM provides a variety of applications for different stages of the construction process, it has a limited ability to address all problems that stakeholders face. To complement its functionalities and support the construction industry in overcoming specific challenges, numerous plugins have been developed for BIM tools by researchers and developers. Previous research has introduced many plugins in several subject areas; energy consumption (Singh, Singaravel, Klein, & Geyer, 2020), health and safety (Rodrigues, Antunes, & Matos, 2021), supply chain management (Chen & Nguyen, 2019), life cycle energy consumption (Kazado, Kavgic, & Eskicioglu, 2019), waste management (Jalaei, Zoghi, & Khoshand, 2021), maintenance (Liu & Issa, 2014), estimation of environmental impacts (Sameer & Bringezu, 2021) and constructability (Kannan & Santhi, 2018). Further examples and plugin development processes can be investigated in detail in the study of Saad, Ajayi, & Alaka (2023).

3.4.3.2 Digital twin

The first three industrial revolutions lasted for nearly two centuries. Industry 1 marked the introduction of water and steam-powered mechanical facilities, while Industry 2 witnessed the application of electrically powered mass production technologies through the division of labor. Industry 3 saw the use of electronics and information technology to support further automation systems (Drath & Horch, 2014). With the rapid digitalization of industry and society, Industry 4 brought about the synthesis of current technologies with modern information and communication technologies (Bitkom, VDMA, & ZVEI, 2016).

Industry 4.0 has a ground based on an important technology, namely IoT. IoT can be defined as “the network of physical objects that feature an IP address for internet connectivity and the communication that occurs between these objects and other internet-enabled devices and systems.” (Stroud, 2022). The utilization of IoT provides real-time data collection from physical products, direct communication and collaboration between physical products, connection between physical products and digital services on the Internet, and remote monitoring, control, and upgrading of physical products (Tao et al., 2018). These technologies, which require the combined potential of artificial intelligence, robotics, and cyber-physical systems, led to the emergence of a new concept; the Digital Twin. The concept of Digital Twin was first coined by John Vickers, an engineer at NASA, in 2003, and popularized by Michael Grieves with his presentation at the University of Michigan (Anderl, Haag, Schützer, & Zancul, 2018). Although the term is often referred to as Digital Twin (Grieves & Vickers, 2017), synonyms such as product avatar or cyber-physical equivalence are also present in existing literature (Holler, Uebernickel, & Brenner, 2016).

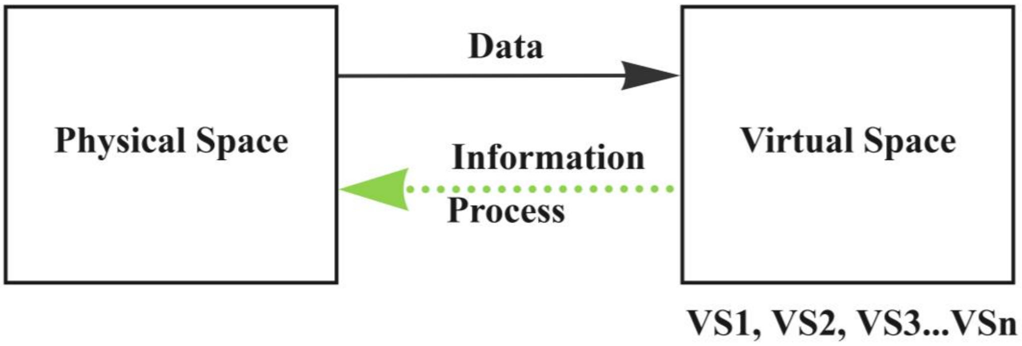


Figure 3.22. Digital twin concept (Adapted from Grieves & Vickers, 2017)

Just like BIM, Digital Twin can also be defined in a narrow or broad sense. In its narrow sense, DT is the answer to the problem of simulating the physical products realistically. In its broad sense, DT acts as an integrated system in which simulation, monitoring, regulation, and control of the system and process occur (Zheng, Yang, & Cheng, 2018). National Aeronautics and Space Administration (NASA) defined DT as “an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin” (Shafto et al., 2010, p.7). As illustrated in Figure 3.22, the DT concept is composed of three main components (Grieves & Vickers, 2017; Zheng et al., 2018), which are:

- *Physical Space* includes a dynamic production environment with people, machines, materials, and rules. All kinds of objects are connected by IOT Technology.

- *The Information Processing Layer* includes a channel connecting physical space and virtual space, bidirectional mapping, and interoperability of physical space and virtual space through the data interaction.

- *Virtual Space* includes two parts the virtual environment platform (VMP) and the DT application subsystem (DTs). VMP provides various virtual models for DTs, including polyphysical models, workflow models, and simulation models; and DTs use this data to accumulate various models and methods (Zheng et al., 2018).

Digital Twin first emerged in the aerospace industry, focusing on structural mechanics, material science, and performance prediction of air and space crafts (Tuegel, Ingraffea, Eason, & Spottswood, 2011). NASA and the US Air Force applied it in vehicle development (Glaessgen & Stargel, 2012). The US Air Force used DT to forecast the structural life of aircraft (Tuegel et al., 2011). General Electric proposed a DT concept for the prediction of product health during its lifecycle (Tao et al., 2018) and Tesla developed a DT for every car to ensure synchronous data transmission between cars and their factories (Schleich, Anwer, Mathieu, & Wartzack, 2017).

Application areas of Digital Twin are highly diverse. It can be applied to speed prototyping, testing or validating specific processes, predicting problems, and optimizing solutions. Moreover, Digital twins can be useful for establishing and fixing weaknesses more cost-effectively and safely compared to their physical counterparts (Gaggioli, 2018). Additionally, it can be used to gather feedback from product users since it provides information throughout the entire product lifecycle (Rosen, Von Wichert, Lo, & Bettenhausen, 2015). Digital twinning explores ways to develop the design and maintenance of physical systems. It enables data-driven methods to discretely map these physical systems into digital and computerized reproductions of themselves (Golata, 2018).

Digital Twin differs from both traditional computer-aided design and sensor-enabled IoT. While CAD concentrates on the digital world and IoT focuses on the physical world, DT involves two-way interactions between the digital and physical worlds. The physical product becomes more ‘intelligent’ with the adjustments to its real-time behavior based on the feedback from the virtual product, while the virtual product becomes more ‘factual’ by representing the real-world condition of the physical product (Tao et al., 2018). Today’s models can represent the product in detail and possess information about performance through advanced simulation methods, but they only serve as blueprints. DT provides a real-time connection between physical and virtual products (Anderl et al., 2018). Given these circumstances, DT is accepted as the next wave of simulation, modeling, and optimization (Rosen et al., 2015) (Figure 3.23).

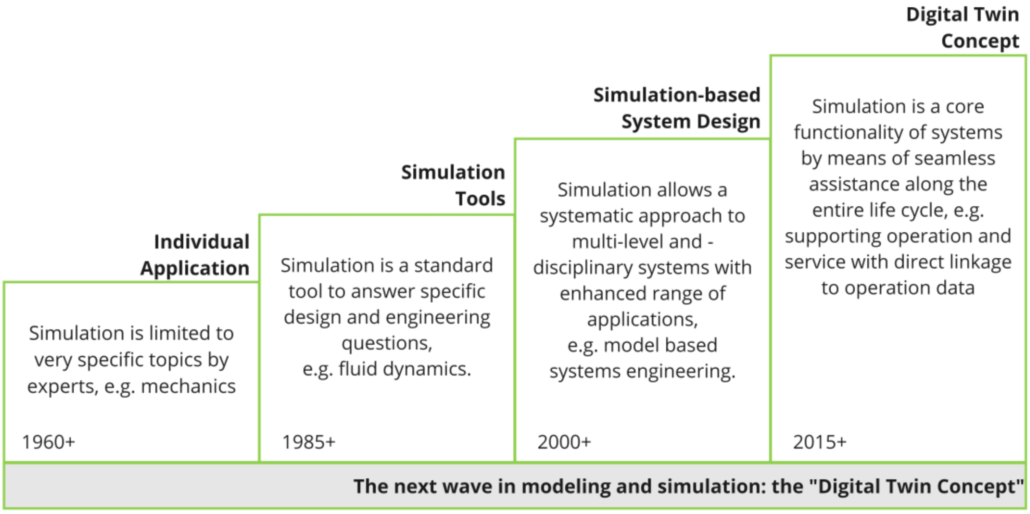


Figure 3.23. The digital twin-the next wave in simulation technology
(Adapted from Rosen et al., (2015))

The study of Khajavi, Motlagh, Jaribion, Werner, & Holmström (2019) presented a comparison of BIM and DT across various dimensions including focus, users, supporting technology, and software to enhance a better understanding of the subject (Table 3.3).

Table 3.3. Digital twin architecture in the built environment (Khajavi et al., 2019).

	Application Focus	**Users**	**Supporting Technology**	**Software**
Building Information Modeling	- Design visualization and consistency - Clash detection - Lean Construction - Time and cost estimation - Stakeholders` interoperability	- AEC - Facility Manager	- Detailed 3D Model - Common data environment - Industry Foundation Class - Construction Operations Building - Information Exchange	Revit Microstation ArchiCAD Open Source BIMserver Grevit
Digital Twin	- Predictive Maintenance - Tenant comfort enhancement - Resource consumption efficiency - What-if analysis - Closed-loop design	- Architect - Facility Manager	3D Model WSN Data Analytics Machine Learning	Predix Dasher 360 Ecodomus

The basic architecture of digital twins includes sensors and actuators from the physical world, integration, data, and analytics (Parrott & Warshaw, 2017). The flow between these elements is demonstrated in Figure 3.24 and they can be briefly explained as:

(i) *Sensors:* To capture the operational and environmental data from physical twin and to create signals;

(ii) *Data:* Real-world data from the sensors and imported data such as drawings, external data feeds, customer complaint logs, and the bill of the materials

(iii) *Integration:* Communication interfaces between the physical world and the digital world

(iv) *Analytics:* Analysis of the data through algorithmic simulations and visualization that digital twin produces insights

(v) *Actuators:* The feedback mechanism of DT to the real world.

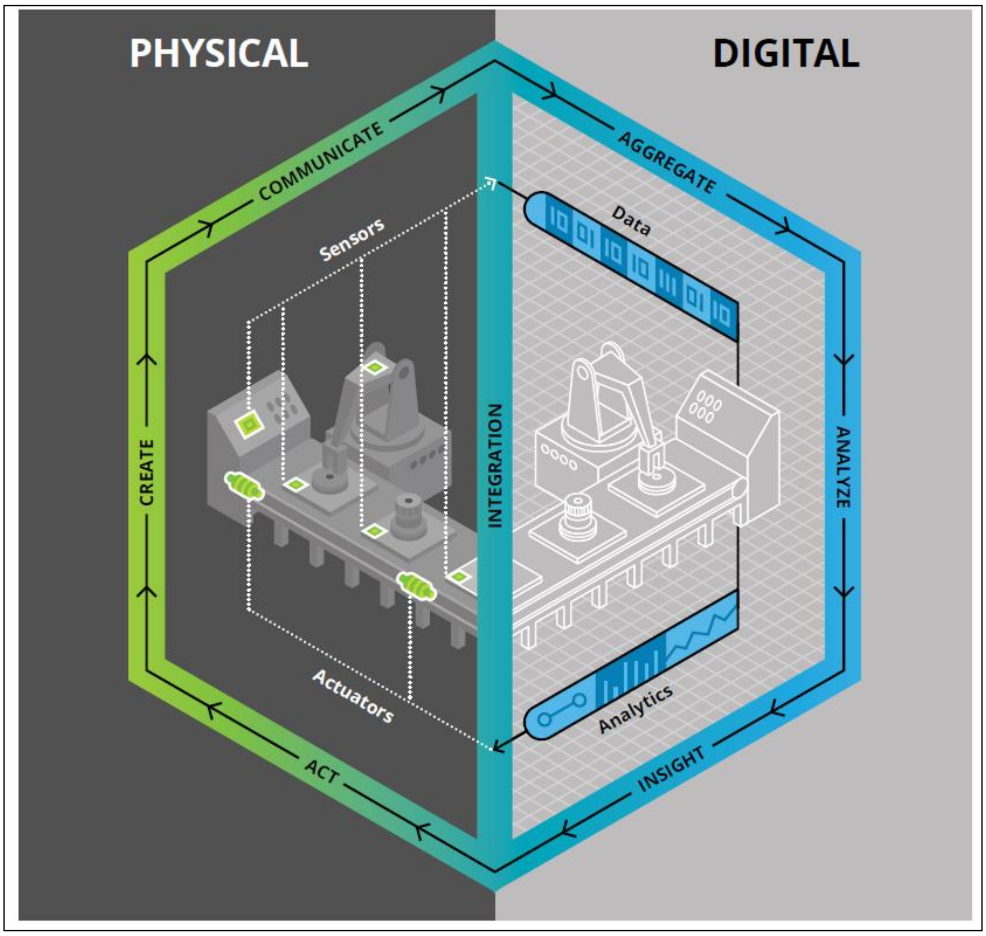


Figure 3.24. The basic architecture of digital twin (Parrott & Warshaw, 2017)

Tools that provide digital twinning include pairing technologies, cyber-physical systems, augmented, virtual, and mixed reality, and artificial intelligence. Pairing technologies allow a device or system to identify, connect, and communicate with other devices and systems, while cyber-physical systems focus on providing the proper utilization of collected data from multiple systems across various disciplines. Augmented, virtual, and mixed reality merge the digital content and physical space, whereas artificial intelligence provides solutions for examining large amounts of digital data (Golata, 2018).

DT manages the available data and produces potential insights using them. Understanding the available data structures in the built environment is vital, as they have a direct influence on the capabilities of DT. Generally, data structures for DT are categorized under two main headings:

- *Breadth:* Digital Twin analyzes data related to construction information, maintenance records, current health, ownership status, financial data, and time-series data obtained from various smart meters, sensors, and digital devices. Additionally, it works with contextual data such as weather conditions, data from behavioral sciences, sentiment analysis from social media, or inputs from wearable technologies.
- *Depth:* Digital Twin takes information from the history of data over time. Historical data can be used to forecast the future using machine learning algorithms. Historical data includes performance and maintenance records, weather data, and usage patterns. Examination of asset performance with historical data enables a strong base for future behavior and identification of anomalies (Woods & Freas, 2019).

The application scale of Digital Twin can change based on the case. The hierarchical structure of Digital Twin frames the potential application ranges in the built environment. Accordingly; there are four distinct levels of DT implementation in the built environment (Figure 3.25): *(i) Single-asset twin:* representing a digital twin of a single asset as an HVAC unit, boiler, or elevator; *(ii) Building twin:* encompassing individual single-asset digital twins within a specific building; *(iii) Community-wide twin:* comprising the individual twins of a portfolio of buildings such as those within a district, or university campus and other relevant models, such as the energy grid, water systems, or transport networks; and *(iv) City-wide twin:* extending to twins for multiple communities, as well as those for city-wide infrastructure and networks (Woods & Freas, 2019).

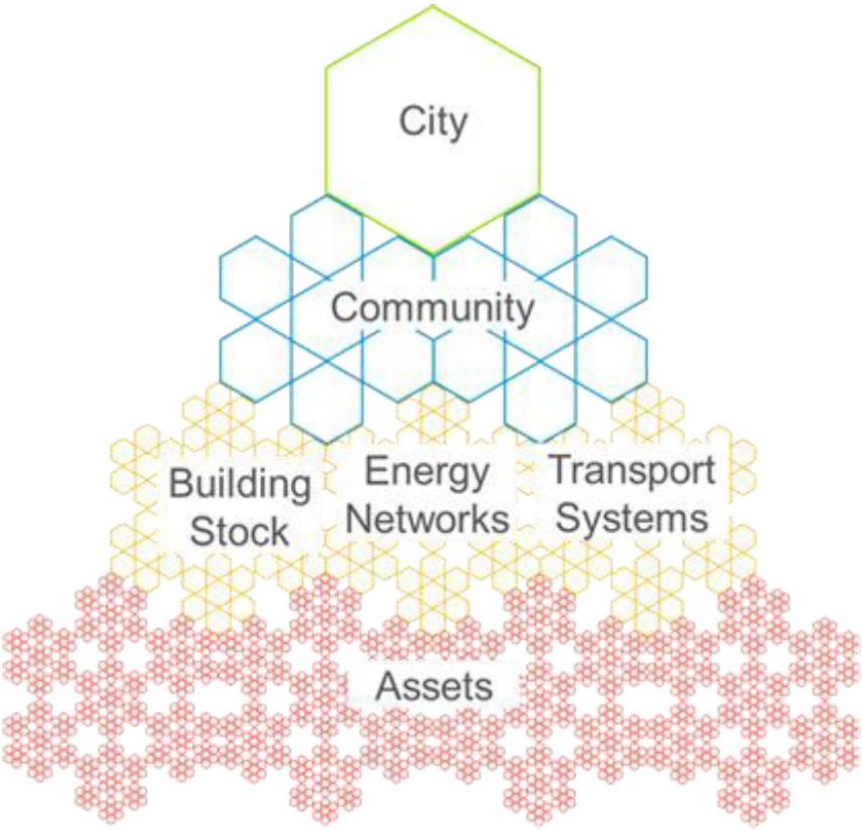


Figure 3.25. The hierarchy of DT implementation (Woods & Freas, 2019)

Figure 3.26 demonstrates the digital twin architecture in the built environment proposed by Khajavi *et al.* (2019). In their model, necessary data components including data structures, 2D/3D drawings, and documents from the related software are consolidated. By merging the real-time operational data at gateway nodes, data is prepared for integration and analysis using machine learning algorithms. Analyzed data provides insights into the physical twin. In this case, the virtual twin provides feedback to the physical twin about predictive maintenance, improvement of building operations and use cycle, and what-if analysis. Parallel to what Khajavi et al.(2019) presented, Tao *et al.*(2018) stated that wireless sensor network integration and data analytics are two main components required to create a digital twin. In order to delve deeper into the architecture of the digital twin system, the next sections focus on sensor network requirements and data analytics methods in the built environment.

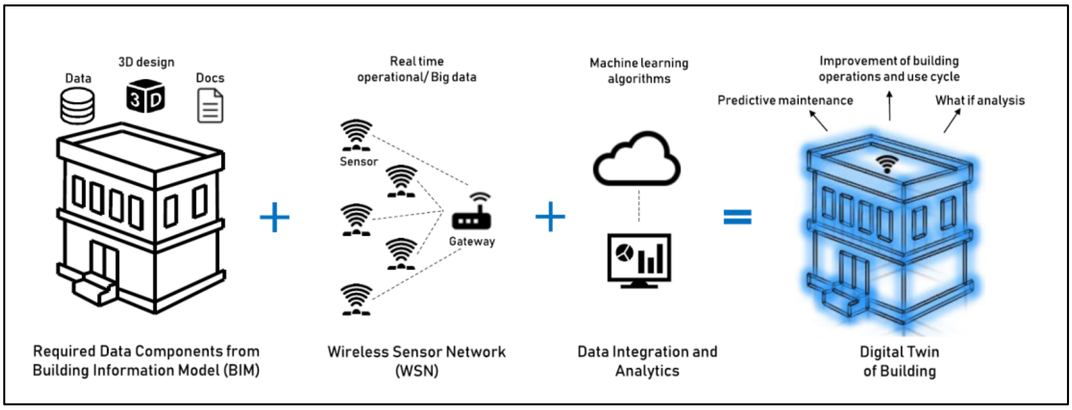


Figure 3.26. Digital twin architecture in the built environment (Khajavi et al., 2019)

Sensor network

Buildings are constructed with diverse monitoring and control subsystems for several reasons such as providing indoor comfort in multiple domains, creating healthy environments, and saving energy (Včelák, Vodička, Maška, & Mrňa, 2017). Sensor studies transformed various industries as technology develops. In the context of intelligent building operations, sensors are divided into three categories (Table 3.4). The categories involve sensors to detect the occupant's existence in space, analyze the existing environmental conditions, and understand occupant behavior (Dong, Prakash, Feng, & O’Neill, 2019).

Table 3.4. List of sensors for intelligent building operations (Dong et al., 2019).

Category	**Sensor types**
Occupancy sensors	Image-based sensors, passive infrared sensors, radio-based sensors, threshold and mechanical sensors, chair sensors, pressure mats, camera sensors, photo sensors, ultrasonic doppler, microwave doppler, ultrasonic ranging
Building environment measurements	CO_2 sensor, Air temperature sensor, humidity sensor, thermo-fluidic sensor, sound sensor, light sensor, volatile organic compound sensor, particulate matter sensor, air velocity sensor
Other sensors	Wearable sensors, IoT-based sensors, smartphones, heart rate sensors, fingerprint sensor, mobile pupilometer, skin temperature sensor

Types of sensors under these three categories are as follows:

Occupancy sensors

- *Image-based sensors* produce the dots of signals and analyze the background in space. Once the signals hit an object, it reflects them. It is used to locate occupancies (Seer, Brändle, & Ratti, 2014). Examples: Infrared (IR) cameras, visible light cameras, and luminance cameras (Dong et al., 2019).
- *Motion sensors* are used to understand the occupancy presence. Examples: Passive infrared sensors, ultrasonic dopplers, photo sensors, microwave dopplers, and ultrasonic ranging (Dong et al., 2019).
- *Radio-based sensors* are used to determine the occupant's presence and to understand movement, count, and identity (Misra & Enge, 2006). Examples:

RFID, WIFI or Bluetooth, a global positioning system (GPS), and ultra-wideband (UWB) (Dong et al., 2019).

- *Threshold and mechanical sensors* determine the occupant's presence in the case of interaction with windows /doors or other occupants (Caucheteux, Es Sabar, & Boucher, 2013). Examples: Reed Contacts, door badges, piezoelectric mats, and IR beams (Dong et al., 2019).

Building environmental sensors

- *Temperature and humidity sensors* measure indoor environmental characteristics. Examples: temperature sensors, humidity sensors, thermo-fluidic sensors, automated mobile sensors (Dong et al., 2019).
- *Air velocity sensors* are employed for the measurement of the airflow rate in the built environment (Dong et al., 2019).
- *Photometric sensors* are utilized for the control of luminaire intensity in terms of daylight availability (Navada, Adiga, & Kini, 2013).
- *CO_2 sensors* analyze the correlation between the occupant's presence and the concentration of CO_2 in the air exhaled by the occupants (Nassif, 2012).
- *Volatile organic compounds (VOC) sensors* are used to analyze the concentrations of gaseous materials in the built environment and to understand the indoor air quality of the space (Dong et al., 2019).
- *Particulate matter (PM) sensors* measure the concentration of particles in the indoor air (Dong et al., 2019).
- *Water sensors* are used to evaluate leak detections near sinks, showers, and other water points (Havard, McGrath, Flanagan, & MacNamee, 2018).
- *Level sensors* are utilized for the sensation of liquid level that indicates the potential flooding in buildings. They are recommended for rooms that have

pipes or are not heated well or insulated (Sood, Sandhu, Singla, & Chang, 2018; Verma, Prakash, Srivastava, Kumar, & Mukhopadhyay, 2019)

- *Touch sensors* are developed to sense touch or proximity. The common usage of this type of sensor is to replace mechanical buttons in buildings/remote controls/control panels (Verma et al., 2019).
- *Moisture monitoring sensors* are embedded into the structural systems of buildings when there is a risk of damage to the material due to moisture. Example: Moisture Prevention for Wood Structure (Moistureguard) (Včelák et al., 2017).
- *Corrosion sensor:* The sensor and structural system of the building are merged to detect the probability of corrosion in reinforced concrete (Calvo Valdés, Medeiros, & Macioski, 2021).

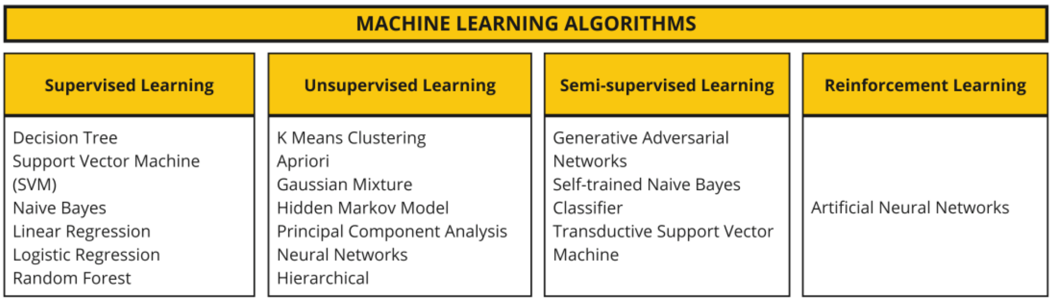
Other sensors

- *Wearable sensors* are used for collecting individual occupancy data. Skin temperature, location, air temperature, relative humidity, and heart rate can be detected (Abdallah, Clevenger, Vu, & Nguyen, 2016).
- *Internet of Things-based sensors* include the determination of the occupancy presence and comfort conditions with the help of a communication network between the existing devices. Examples: smartphones, wearable devices, IoT-based thermostats, and light control units (Dong et al., 2019).

Machine learning algorithms

Arthur Samuel, credited as the founder of Machine Learning (ML), defined it as an area of study that "gives computers the ability to learn without being explicitly programmed" (Manesh, 2020). The working mechanism of ML algorithms involves a computer program executing defined tasks, with the expectation that the machine learns from its experiences and improves its ability to perform these tasks over time. Ultimately, the machine can make decisions or assist in creating decision-making systems to predict or forecast outcomes based on the available data (Dhall, Kaur, & Juneja, 2020; Ray, 2019). Addressing data problems requires employing different algorithms, as there is no one-size-fits-all solution. The choice of algorithm depends on factors such as the nature of the problem, the number of variables involved, and the type of model that would best fit the problem (Manesh, 2020). There is a wide range of application fields for ML, including robotics, virtual personal assistants, computer games, pattern recognition, natural language processing, data mining, traffic prediction, online transportation networks, e-mail spam filtering, crime prediction, social media services, and medical diagnosis (Das, Dey, Pal, & Roy, 2015; Ray, 2019).

Over time, a diverse array of ML algorithms have been developed, each serving different purposes but often employing common approaches to problem-solving. These approaches involve classification, regression, and clustering (Ray, 2019). To address the research problems at hand, it is essential to study the most relevant ML algorithms. There are multiple studies available in the literature for a deeper understanding of various ML algorithms (Dey, 2016; Dhall et al., 2020; Manesh, 2020; Osisanwo, et al., 2017; Sarker, 2021). Broadly, ML algorithms can be categorized into four main types: supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning. The wide-ranging applications of ML algorithms are illustrated in Figure 3.27.



MACHINE LEARNING ALGORITHMS

Supervised Learning	**Unsupervised Learning**	**Semi-supervised Learning**	**Reinforcement Learning**
Decision Tree Support Vector Machine (SVM) Naive Bayes Linear Regression Logistic Regression Random Forest	K Means Clustering Apriori Gaussian Mixture Hidden Markov Model Principal Component Analysis Neural Networks Hierarchical	Generative Adversarial Networks Self-trained Naive Bayes Classifier Transductive Support Vector Machine	Artificial Neural Networks

Figure 3.27. Machine learning algorithms (developed by the author)

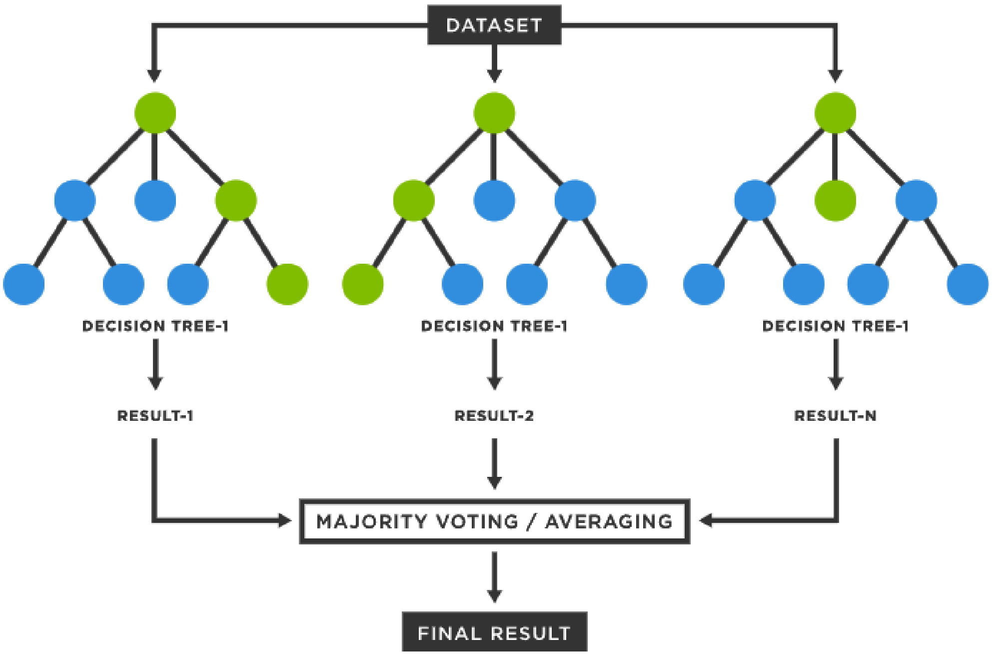


Figure 3.28. Random forest learning model working mechanism (TIBCO, n.d.)

Within the context of this study, supervised learning is particularly relevant to the defined scope. The definition of supervised learning was made as "the machine learning task of learning a function that maps an input to an output based on example input-output pairs" (Manesh, 2020). Supervised learning involves training the machine by presenting it with input-output pairs in training datasets to discern patterns within the data. Decision tree, support vector machine, Naïve Bayes, linear regression, classification (logistic regression), and random forest are the common supervised learning algorithms. They can be explained shortly as follows:

- *Decision Tree:* It is a classification model to represent choices and their results in the form of a tree (Manesh, 2020)
- *Support Vector Machine (SVM):* It is a classification model that evaluates the results with margins between the classes (Dhall et al., 2020).
- *Naïve Bayes:* The underlying principle of this clustering and classification model is based on conditional probability (Dey, 2016).

- *Linear Regression:* It is used to develop a response B from the predictor variable A accepting the existence of the linear relationship between A and B (Dhall et al., 2020).
- *Classification/ Logistic Regression:* It is a learning model used for classifying two or more classes. The result is either a yes (1) or a no (0) (Dhall et al., 2020).
- *Random Forest (RF):* This model uses parallel ensembling, which evaluates several decision tree classifiers in parallel to make a prediction (Sarker, 2021). The computing procedure of a random forest algorithm is given in Figure 3.28.

3.4.4 Critical disposition of the architectural detailing in digital age

As described in previous sections, each digital tool offers different capabilities to the architects throughout the architectural design phase. Despite these advancements, there are still bottlenecks in guiding the architects during the early design phase to make them respond to the changing needs of the use phase. These problems arise due to several factors inherent in the architectural design process and its interaction with digital design tools. The architectural design process typically follows a whole-to-parts approach by increasing the levels of detail at each phase. In such end, architectural detailing is often treated as the technical aspect of the building structure, and selected from a component library within digital design tools. However, architectural detailing should be considered from the beginning of the architectural design process. and architects should control the design by defining the relationships from smallest scale to systems scale to enhance building adaptability. The evaluation of the decomposition of building structures is required in the architectural design process to provide the architects with better control. Considering the capabilities of digital design tools and architectural design process, integrating decomposition thinking into building designs is necessary to foster systematic thinking.

Digital design tools provide component packages to support the architects during the selection process of the architectural detailing. While these component packages standardize the building elements, they often lead to the creation of rigid building structures due to the lack of transformability of these components. Moreover, current digital design tools lack the capability to support architects at the smallest scales due to their inherent limitations. Creating fixed building structures in the early design process affects the use phase of the buildings by preventing future transformations in building elements and spaces. Despite the inevitability of maintenance and repair throughout a building's lifecycle, these considerations are often overlooked in the early design phases. This oversight results from improper architectural design processes and the lack of architectural detailing evaluation in digital design tools. Although cutting-edge technologies provide real-time data transfer and hyper-realistic modeling, there is no feedback mechanism to support the architectural design process effectively.

Architects need essential feedback from digital design tools to support the design decisions related to the architectural detailing from the early phases. Feedback is crucial to develop any process. Feedback can be defined as the information given by a source (such as a teacher, peer, book, parent, self, or experience) regarding various aspects of one`s performance or comprehension. A teacher or parent can enhance corrective information, a peer can suggest a different approach, a book can offer explanations to clarify ideas, a parent can encourage, and a learner can seek answers to evaluate the accuracy of a response (Hattie & Timperley, 2007). Although most of the studies in the literature using feedback systems are produced in educational research, they originated in the engineering field (Wiliam, 2012). While educational research handles feedback systems as a form of positive reinforcement in learning, engineering accepts it as a part of a system (Wiliam, 2012). A feedback mechanism is essential in the architectural design process to support architects' decision-making, particularly concerning architectural detailing. This mechanism requires a reexamination of current digital tools, focusing on their capabilities and contributions.

CHAPTER 4

A COMPONENT-ORIENTED STRATEGY

Understanding the complex systems` behavior and the rules of their components needs a comprehensive system analysis at different scales. In these systems, there are various interrelations at multiple levels from element to whole. Given that system architecture design hinges on elements, their attributes, and their (inter)relations (Fricke & Schulz, 2005), it's imperative to recognize that relationships within building structures at the component level cannot be assessed in isolation from systematic relationships. A change in a single element may have repercussions throughout the entire system. The relationships between components may be more complex than they appear at first glance. Revealing the dependencies between components and understanding the system's behavior on multiple scales is crucial for understanding the architecture of complex systems. This study proposes an architectural detailing strategy, aiming to analyze and improve relationships at the component level to achieve waste-free transformation in building structures. Such an approach places emphasis on the elements and evaluates their positioning within both system and component scales.

In this chapter, a component-oriented decision-making strategy is proposed to accommodate potential changes in building components throughout the building life cycle. The suggested framework will enhance the improved adaptability of buildings by aiding architects in the design phase with alternative selections in component scale. It will also lead to improvements in the use phase of buildings by informing occupants about the methods of building structure’s transformability and efficient timing for maintenance and change. It also underlines the importance of detailing selection for the whole building lifecycle by presenting the potential consequences related to a circular economy and sustainability understanding.

This section starts with a general description of strategy generation, outlining the fundamental phases of synthesis, model, and implementation. It then demonstrates the practical application of the strategy to present the implementation of the strategy with architectural details. The strategy is further elaborated to explain the essential steps, presenting an exemplary workflow with an architectural detail example for the design phase and a case study for the use phase.

4.1 Generation of the strategy

A component-oriented strategy aims to enable transformability in building structures by controlling the building relationships and dependencies at both systems and component scales. The developed model of this strategy is applicable to any building system, facilitating decision-making in architectural details. Before presenting a practical example, it is crucial to understand the general structure of the strategy.

The suggested model can be explained in three steps: synthesis of core information, model development, and implementation of the model. The synthesis step includes an explanation of the base elements, previously discussed in earlier chapters, necessary for proposing the model. the model development step outlines key phases, methodologies, and an outline of the decision-making strategy that allows for transformations throughout a building`s life cycle. Lastly, the implementation step presents how the proposed strategy is applied to practical examples.

4.1.1 Synthesis of core information

In this step, the core information of the research was synthesized and analyzed for model development. This involves assessing the architectural detailing process, using decomposition approaches at multiple scales, evaluating component dependencies, defining feedback mechanisms, developing interfaces for digital design tools, and establishing the necessary infrastructure for real-time connectivity.

The architectural design process was evaluated focusing on the role of architectural detailing and its relations at both macro and micro scales. This multi-scale evaluation brought about the decomposition approaches of the building structure from system scale to component scale. These approaches were compiled in a mechanism called assembly library. At the system scale, decomposition evaluates relationships using the layer model of Brand (1994), while at the component scale, it employs the decomposition aspects of Durmisevic (2006). When breaking down the components, it was crucial to utilize a suitable methodology to analyze the relations between building components. To this end, the Design Structure Matrix was employed in the breakdown of the building structure to examine the dependencies of building components.

Feedback mechanisms were defined considering the architectural design process, the needs throughout the building life cycle, target users, and design tools. The working mechanism of the designated feedback system was visualized with the anticipated interface for digital tools. It was assumed that the architect would use a BIM tool, and user interfaces were visualized according to the software's representation techniques.

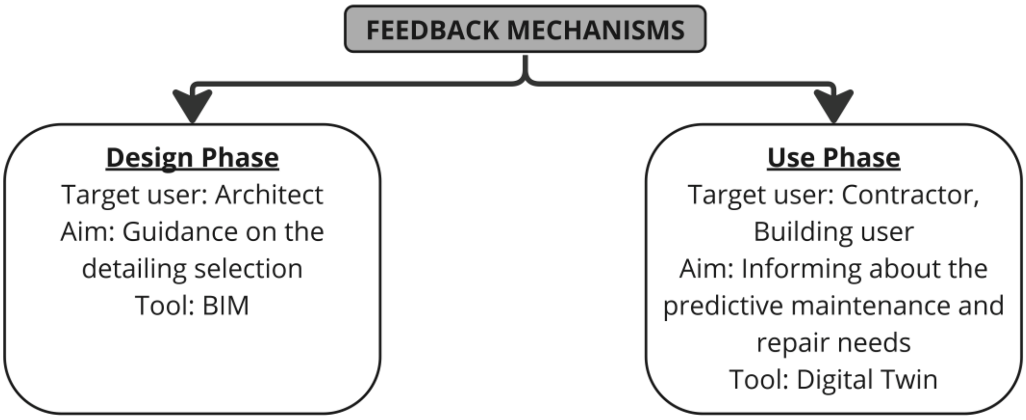


Figure 4.1. Feedback mechanisms in this study

The operational flow of the feedback mechanism during the use phase was presented by associating necessary data sets and sensor networks in a case study. While sensor networking was defined by analyzing the needs of the case, necessary data sets were compiled from various literature sources. In the use phase, target users were defined as contractors and building occupants. Due to the need for real-time connection between the building and the digital system, the required digital tool was defined as

Digital Twin for this stage. In this research, feedback mechanisms were interpreted as guidance systems that help architects and building occupants in different phases of the building life cycle (Figure 4.1).

4.1.2 Model Development

Analysis of the building structure across multiple scales involves the decomposition of building structures. Accordingly, the suggested component-oriented detailing strategy includes three stages in the design phase: development of the system architecture model; unveiling of hidden relations and potential chunks; and utilization of the feedback mechanism, as illustrated in Figure 4.2.

For the initial development of the system architecture model, architectural details were selected and decomposed into elements to unveil the relations. Certain estimations were made in the hierarchical breakdown of the structure. Subsequently, in the second stage, architectural details were analyzed using the Design Structure Matrix. The objective was to expose both hidden and evident relationships between building components and to formulate the chunks by integrating both functional requirements and service life information/maintenance needs. Finally, in the last stage, architectural details were assessed utilizing decomposition aspects at both system and component scales. The analysis is designated to be predicated on the datasets in the assembly analysis library. The potential operational flow of the suggested feedback system, which includes the evaluation of architectural detail by architects, was depicted through an envisioned interface tailored for a commonly used software tool by Autodesk.

In the use phase, feedback mechanisms are suggested to keep building occupants or contractors informed about the maintenance schedules and repair needs. As a real-time connection to monitor unforeseen changes in components is required, the entire system is suggested to be configured with Digital Twin technology. To construct the digital twin architecture, sensor networks, and machine learning algorithms were reviewed and suitable ones were defined.

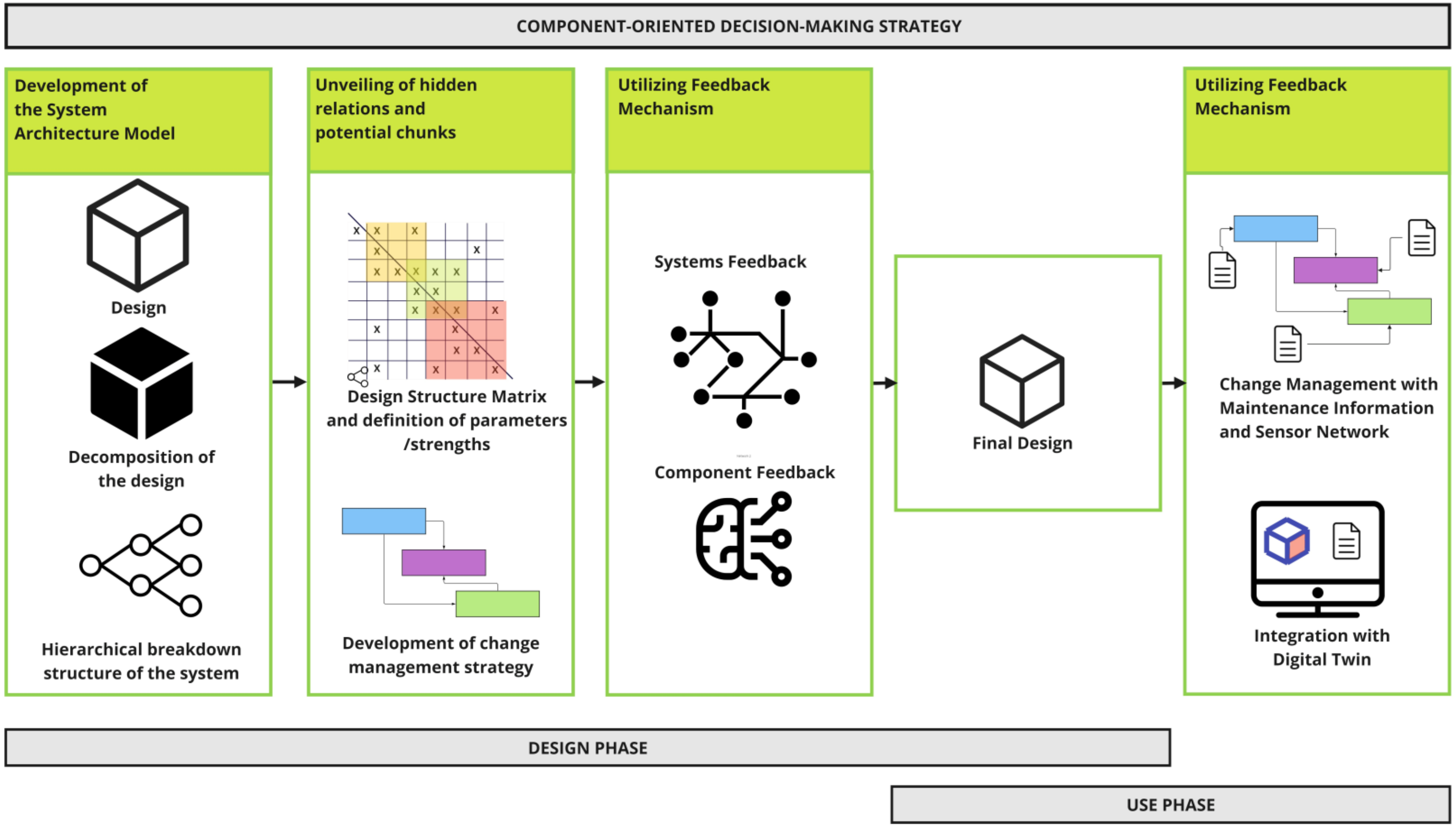


Figure 4.2. The suggested model for component-oriented decision-making (developed by author)

4.1.3 Implementation of the model

The proposed meta-model is developed to be applicable to any building structure and can be adapted to various cases and architectural details. Within the scope of this thesis, a specific architectural detail and its corresponding case were selected for examination. According to the strategy model, this meta-model is utilized by architects during the design phase. Any architectural detail can be selected and evaluated using the proposed strategy in the design phase. Once the building is constructed, a feedback mechanism in the use phase will manage maintenance and repair schedules for the architectural details of the building.

The subsequent section elaborates on the suggested model with architectural detail, outlining the fundamental mechanisms for implementing the strategy in the design phase. Following that, the details of the implementation in the use phase are presented.

4.2 Practical application of the strategy

As a case study, an educational setting in METU was selected for the use phase, and the architectural detailing evaluated is considered part of this setting. In this context, the practical application of the strategy starts with the evaluation of the architectural detail in the design phase to gather feedback. It then demonstrates the relation of that setting with the feedback mechanism in the use phase to support maintenance and repair.

Brick masonry cavity walls, both load-bearing and non-load-bearing assemblies, have been commonly utilized in buildings for a long time. The selected detail, as documented in Boswell (2013), is the non-load-bearing cavity wall assemblies consisting of a brick masonry veneer, a cavity space, and an inner supporting wall. Exterior brick veneer has multiple material options such as concrete masonry units, clay tile, terra cotta, brick, or other human-made masonry units. Cavity space has a range from 50 mm to ½ mm in depth and may or may not contain insulation based on the climate, enclosure, and design responses. The inner supporting wall includes the interior concrete masonry units, concrete wall, heavy gage steel studs, and exterior sheathing assemblies. Figure 4.3 demonstrates the selected detail with zone and component divisions.

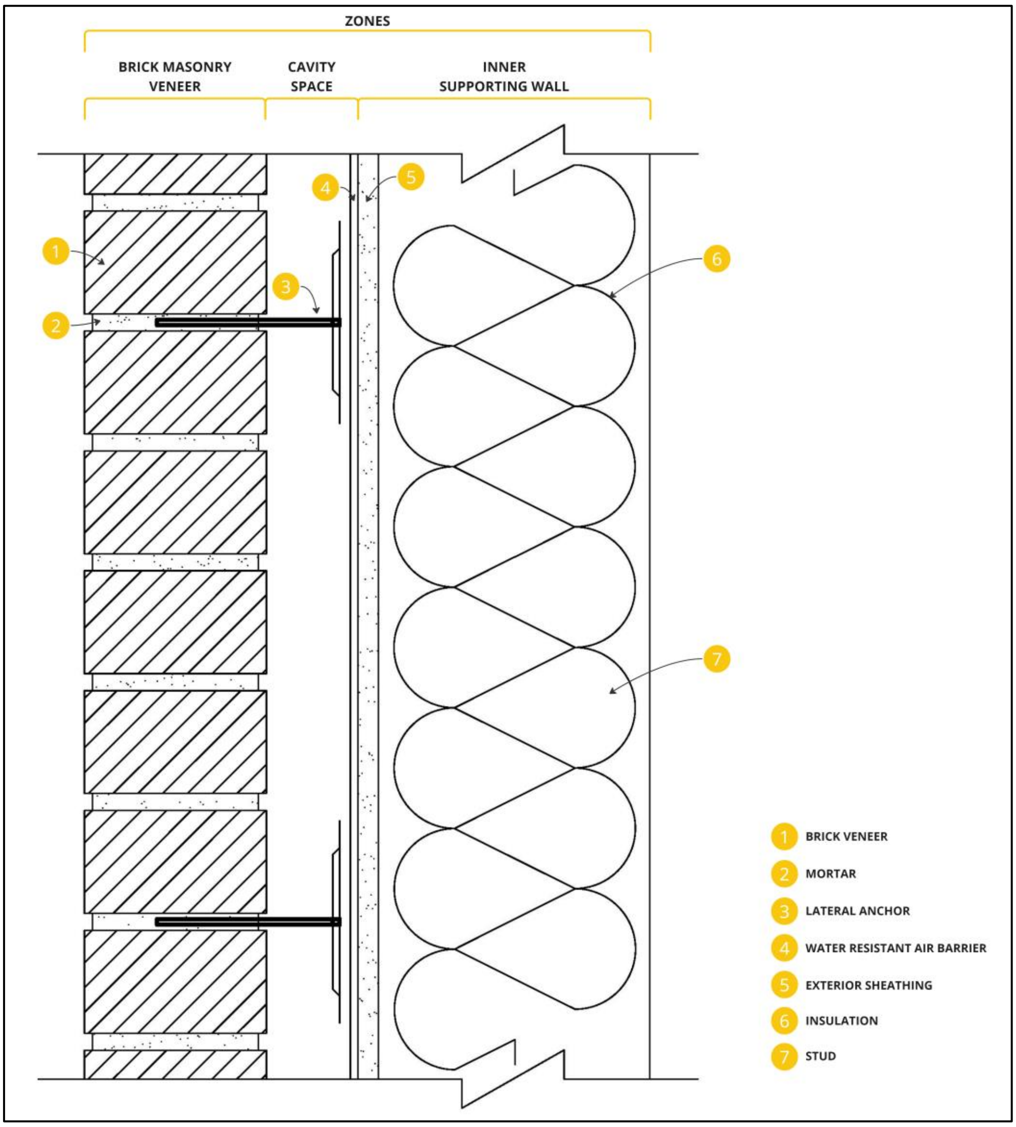


Figure 4.3. The selected detail with zone and component divisions (developed by the author)

In the following subsections, the selected detail is processed through the pillars of the suggested model illustrated in Figure 4.2, including the development of the system architecture model, unveiling of hidden relations and potential chunks, and utilizing feedback mechanisms, respectively.

4.2.1 Development of system architecture model

After the selection of a building detail, the next step was to decompose it into components. In order to analyze the relationships of components and the overall system architecture model simultaneously, tree structures/diagrams were employed. A tree diagram is a visual depiction method to map relationships. It starts with a central node and is developed into branches (Mind Tools Content Team, n.d.). In this study, it is used to expose the hierarchical relationships between the components in the selected architectural detail (Figure 4.4).

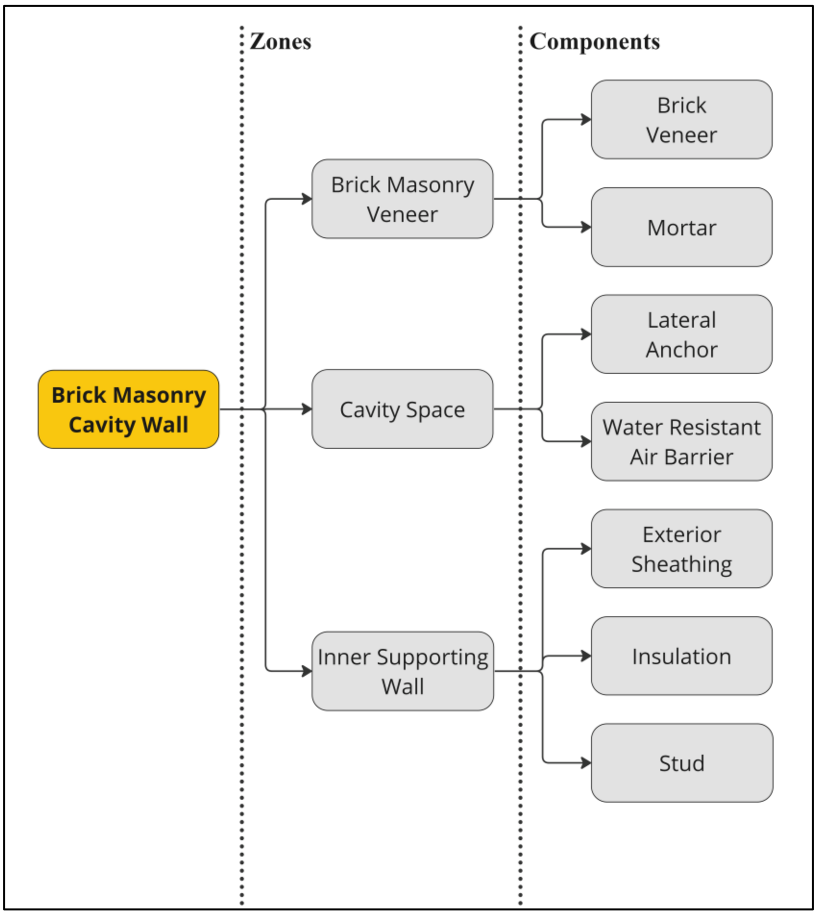
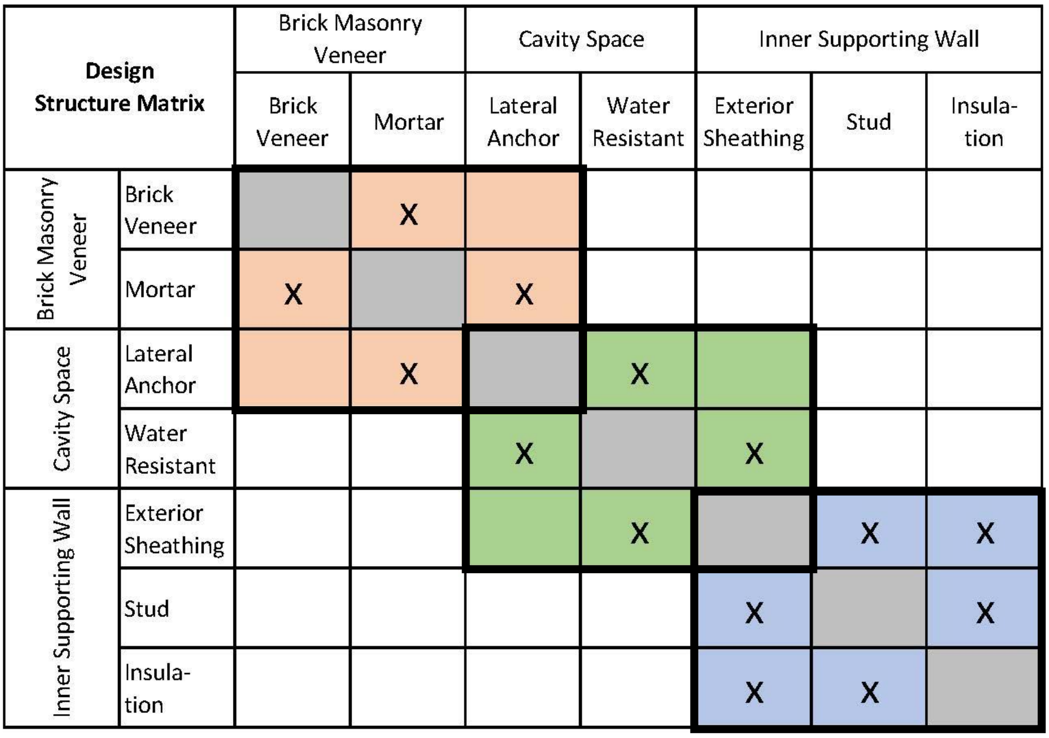


Figure 4.4. Hierarchical breakdown of the system (developed by the author)

Although the illustrated tree diagram shows the hierarchical relations of components and zones, it does not provide any information about the relationships between the elements on the same level, such as the relationships between mortar and brick veneer or lateral anchor and water-resistant air barrier. It is imperative to understand the components` dependencies by exploring the assembly sequences, connection types, and functional requirements. This phase provides a comprehensive understanding of the architectural detail and precedes the unveiling of hidden relations and potential chunks phases. This subsequent phase will elucidate the decomposition of the complex network relations among the components.

4.2.2 Unveiling of hidden relations and potential chunks

The architectural detailing information was extracted from the 2D detail drawing of a brick masonry wall. Initially, the breakdown structure of the detail informed about the component names and their hierarchical relationships. Components were listed and categorized into zones. The dependencies among components are evaluated based on physical relations using the DSM model, which illustrates a network comprising 7 components decomposed into the three preidentified zones (Figure 4.5).



Design Structure Matrix		Brick Masonry Veneer		Cavity Space		Inner Supporting Wall		
		Brick Veneer	Mortar	Lateral Anchor	Water Resistant	Exterior Sheathing	Stud	Insula-tion
Brick Masonry Veneer	Brick Veneer		X					
	Mortar	X		X				
Cavity Space	Lateral Anchor		X		X			
	Water Resistant			X		X		
Inner Supporting Wall	Exterior Sheathing				X		X	X
	Stud					X		X
	Insula-tion					X	X	

Figure 4.5. Component dependency analysis of brick masonry wall with DSM (developed by author)

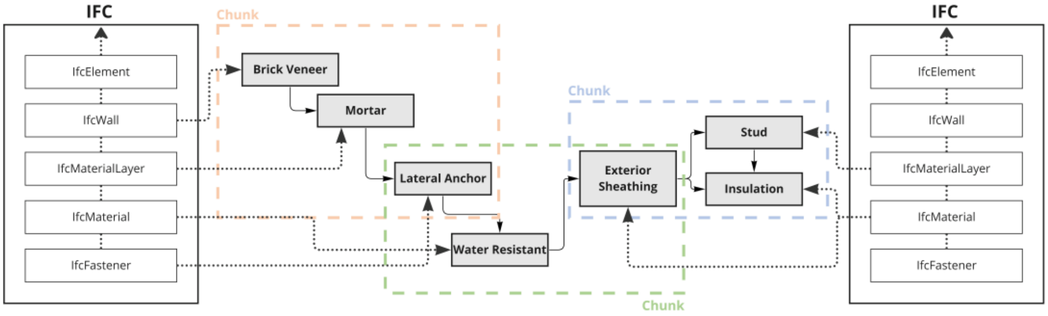


Figure 4.6. Dependency diagram with the Industry Foundation Class (developed by the author)

As a result of DSM analysis, three chunks were identified and shown with the colors orange, green, and blue (Figure 4.5). These chunks exhibit cohesive clustering, and the conjunction areas between the colors, lateral anchor, and exterior sheathing appeared as connection points between the zones. As the aim of adopting the DSM analysis in this study was to illuminate the physical dependencies of components, a dependency analysis was carried out. Connections and dependencies between the components were outlined and results were illustrated in the dependency diagram. To ensure compatibility with digital design tools in future studies, the developed diagram was integrated with the IFC data schema, as illustrated in Figure 4.6.

4.2.3 Utilization of feedback mechanism in the design phase

The proposed model includes two phases for feedback mechanisms: the design and the use. For the design phase, feedback mechanisms were developed considering the systems and component scales. Feedback approaches vary across different scales, offering a range of perspectives to enhance early-stage design. Before delving into the specifics of these mechanisms, it is crucial to configure the foundational infrastructure required to implement them. This infrastructure is supported by two pillars; the assembly library mechanism and the response system. While the assembly library mechanism explains the working principles of the detailing strategy, the response system entails the definition of necessary datasets and feedback explanations.

The assembly library mechanism was developed to define the necessary parameters in the decision-making process. It covers the properties related to the architectural detail, connection details, and assembly process. The assembly library mechanism consists of three steps: development of tree diagrams, assembly analysis library, and decision-making algorithm (Figure 4.7).

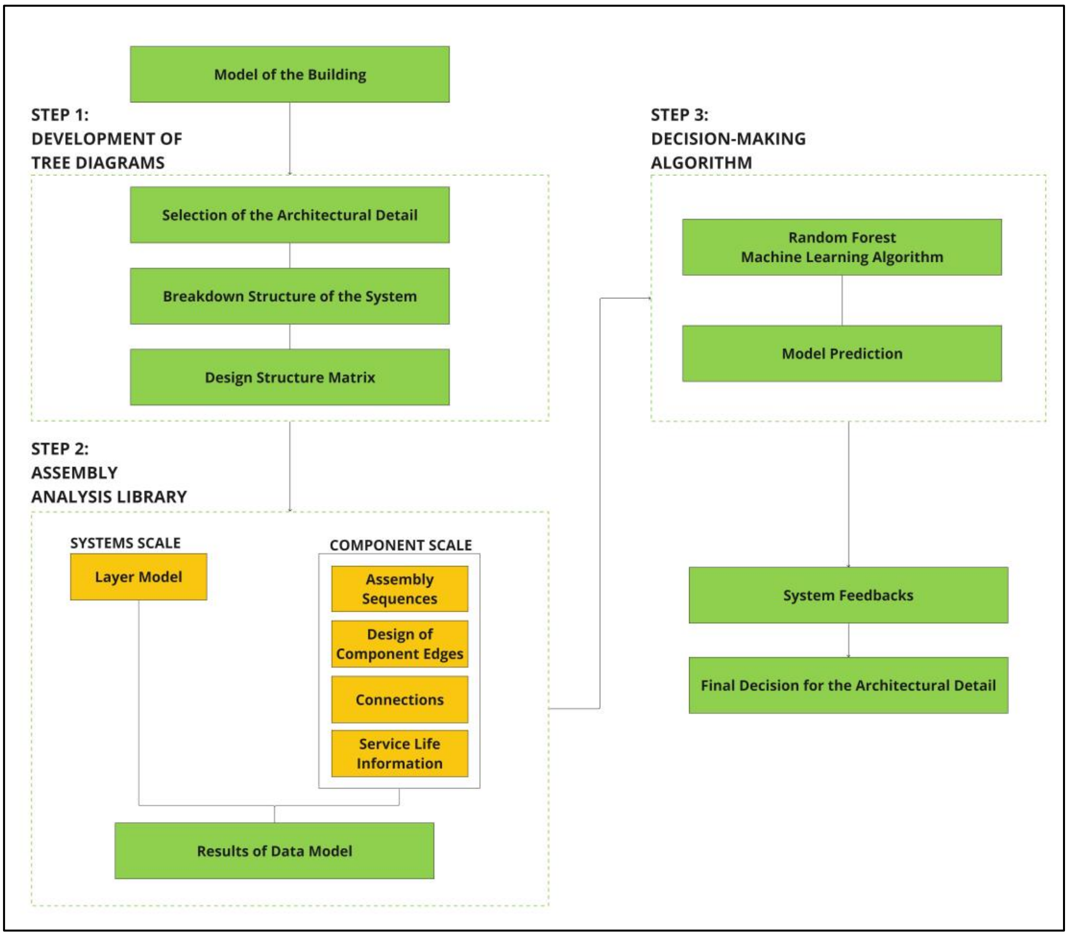
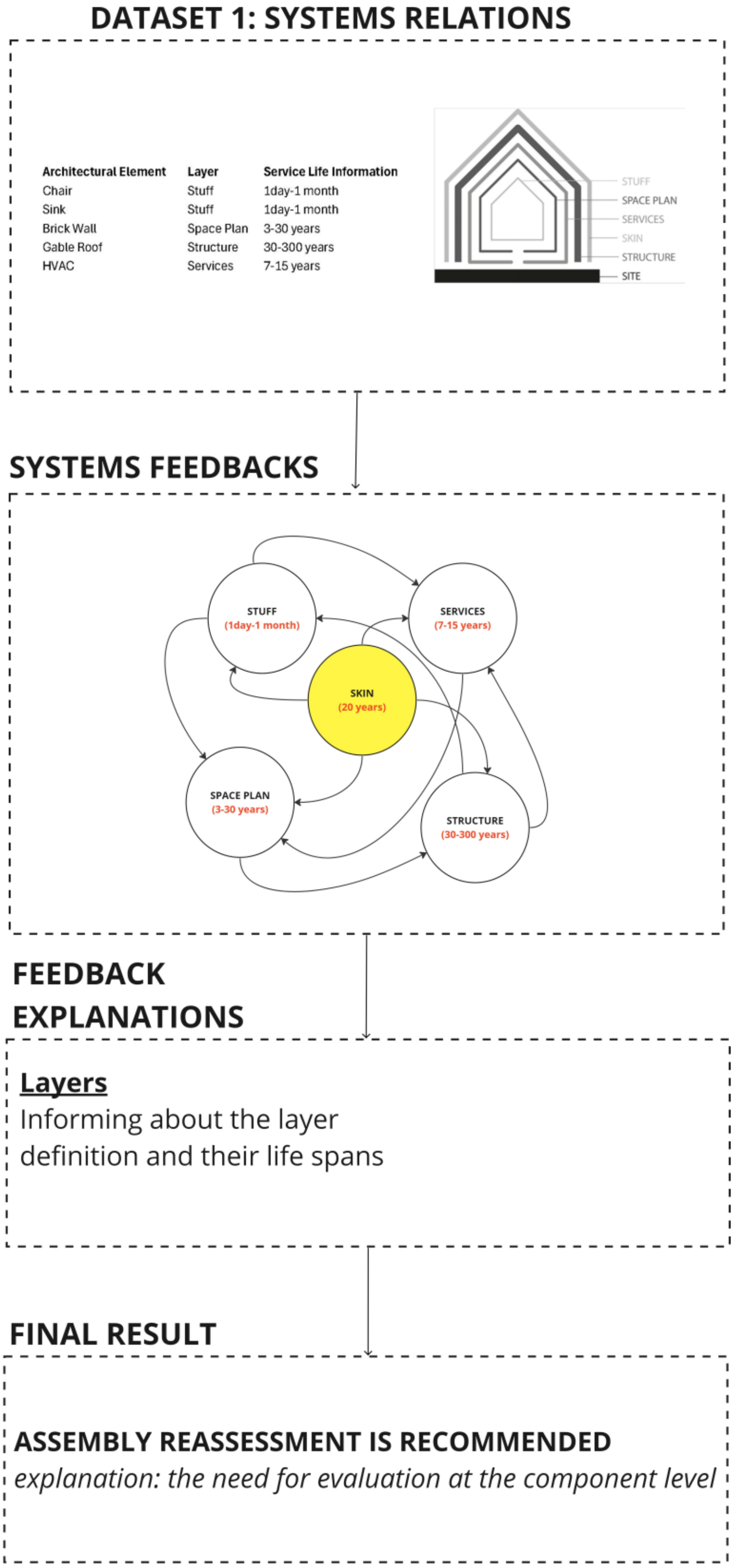


Figure 4.7. Assembly library mechanism (developed by the author)

Development of tree diagrams includes the selection of architectural detail and construction of breakdown structures by using DSM. After the components were presented, and were related to each other, datasets were constructed at systems and component scale. At the systems scale, the dataset encompasses the classification of the layer model. At the component scale, on the other hand, datasets cover assembly sequences, design of component edges, connections, and service life information. The content of the assembly library was constructed using common typologies classifying the majority of the architectural details used in the construction industry. In the decision-making algorithm stage, the selected architectural detail was evaluated by the assembly library. This mechanism is anticipated to facilitate the assessment of the detail and produce system feedback, utilizing the datasets and model prediction feature of the Random Forest algorithm.

The necessary datasets were defined in the assembly analysis library for system relations and component relations. The systems relations section aims to give an overall understanding of the architectural elements to the architect and create an awareness of the service life compatibility between components/ elements at the systems scale. Figure 4.8 frames the working principles of systems relations with a dataset example, relationship diagram, and feedback explanations.

In system relations; the architectural elements, their corresponding layers, and service life information are compiled into a dataset. According to the selected architectural element, the whole system is analyzed, and the relationship of the layer systems is visualized. For example, the brick masonry wall is a type of wall that is placed into the space plan layer and has a 3 to 30-year life span. Based on the selected architectural detail, the mechanism first evaluates the architectural detail to understand its category in layers. After matching the layer definition and architectural element, corresponding service life information is found. With that, layers around the architectural element in the model are analyzed and the relationship diagram is constructed to inform the designer about the interactions between the architectural layers at higher levels. As a final result, a strategy informs the architect by showing the phrase “ASSEMBLY REASSESSMENT IS RECOMMENDED” with an explanation of “*the need for evaluation at the component level”.*



Architectural Element	Layer	Service Life Information
Chair	Stuff	1day-1 month
Sink	Stuff	1day-1 month
Brick Wall	Space Plan	3-30 years
Gable Roof	Structure	30-300 years
HVAC	Services	7-15 years

Informing about the layer definition and their life spans

ASSEMBLY REASSESSMENT IS RECOMMENDED

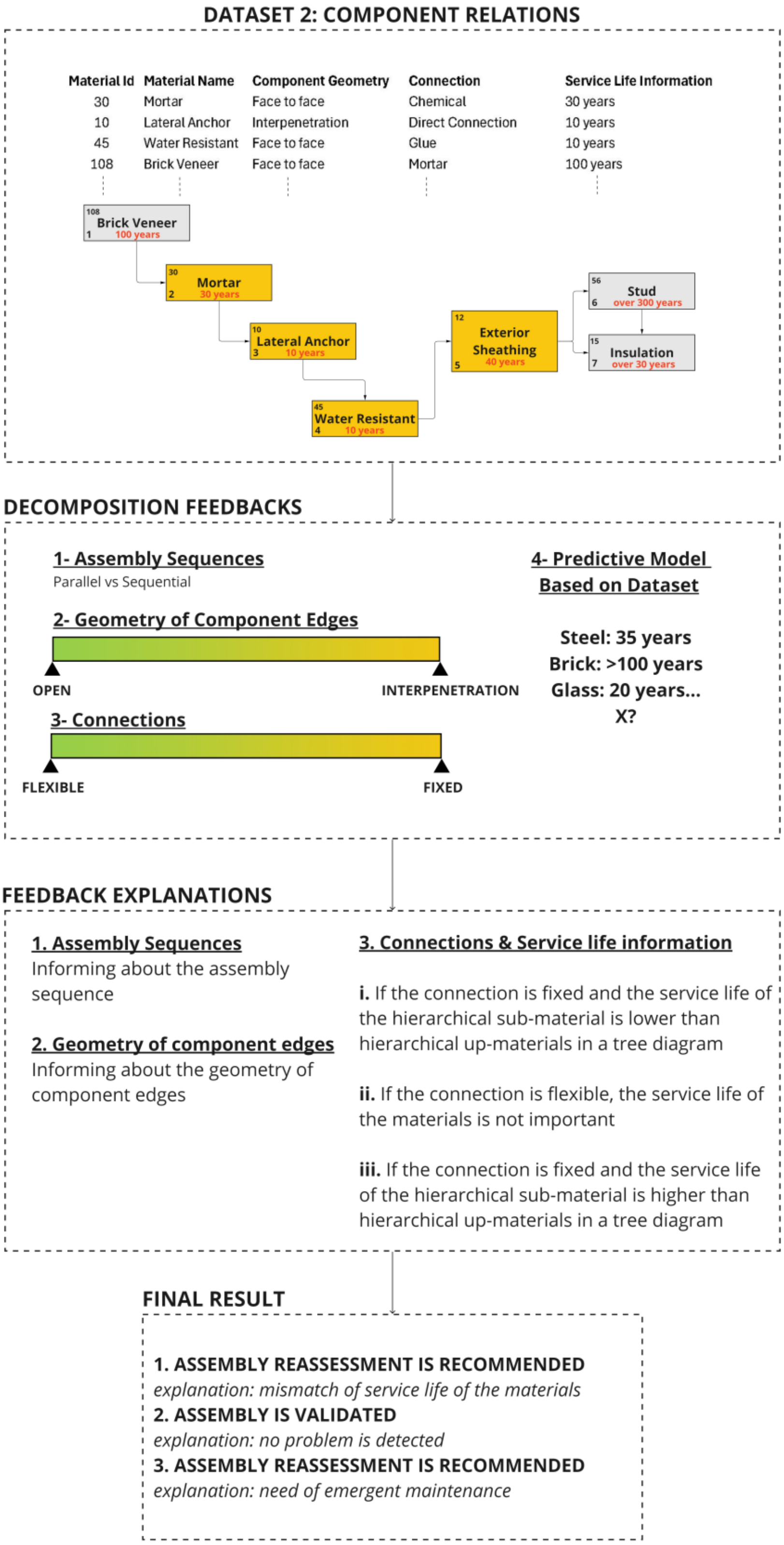
explanation: the need for evaluation at the component level

Figure 4.8. Working principle of systems relations dataset (developed by the author)

The component relations dataset includes the properties of architectural details focusing on the decomposition aspects. Its objective is to offer architects a comprehensive understanding of architectural details and guide them regarding the levels of decomposition in these details. As such, the dataset includes classifications related to assembly sequences, design of component edges, connections, and service life information. Additionally, each material is identified by both a name and an ID within the dataset. By utilizing the dependency diagram developed through DSM and dataset information, relationships between components are visualized using a diagram called material boxes. This diagram aims to merge visual dependency analysis with nominal information in a straightforward manner. Material boxes contain a material name, an ID, a sequence number for the assembly process, and service life information, as demonstrated in Figure 4.9.

Figure 4.9. Material boxes with information packages (developed by the author)

After the selection of architectural detail, component relations were analyzed and the dependency diagram was merged with the information in the component relations dataset, as outlined in Figure 4.10. The mechanism offers decomposition feedback based on the selected decomposition aspect. Within assembly sequences, the dependency analysis illustrates the assembly sequence number in the assembly process, informing the architect about the type of assembly sequences and their potential benefits or drawbacks. The objective is to alert the architect to the dependencies between components arising from the assembly process and to prepare them for the analysis of connections and service life information, which are primary decomposition aspects aimed at enhancing building changeability. It is expected that the architect considers the component selections in architectural detail by minding the assembly process.



DATASET 2: COMPONENT RELATIONS

Material Id	Material Name	Component Geometry	Connection	Service Life Information
30	Mortar	Face to face	Chemical	30 years
10	Lateral Anchor	Interpenetration	Direct Connection	10 years
45	Water Resistant	Face to face	Glue	10 years
108	Brick Veneer	Face to face	Mortar	100 years

DECOMPOSITION FEEDBACKS

1- Assembly Sequences
Parallel vs Sequential

2- Geometry of Component Edges

3- Connections

4- Predictive Model Based on Dataset

Steel: 35 years
Brick: >100 years
Glass: 20 years...
X?

FEEDBACK EXPLANATIONS

1. Assembly Sequences
Informing about the assembly sequence

2. Geometry of component edges
Informing about the geometry of component edges

3. Connections & Service life information

i. If the connection is fixed and the service life of the hierarchical sub-material is lower than hierarchical up-materials in a tree diagram

ii. If the connection is flexible, the service life of the materials is not important

iii. If the connection is fixed and the service life of the hierarchical sub-material is higher than hierarchical up-materials in a tree diagram

FINAL RESULT

1. ASSEMBLY REASSESSMENT IS RECOMMENDED
explanation: mismatch of service life of the materials
2. ASSEMBLY IS VALIDATED
explanation: no problem is detected
3. ASSEMBLY REASSESSMENT IS RECOMMENDED
explanation: need of emergent maintenance

Figure 4.10. Working principle of connections relations dataset (developed by the author)

In the geometry of component edges, an architectural detail is evaluated and feedback is provided with a visual scale from open to interpenetration. The type of geometry of component edges is defined with the diagrammatic explanation. The aim here is to inform the architect about the geometric conditions of the architectural detail and establish a basis for evaluating connections and service life information. The feedback in the assembly sequence and geometry of component edges is specified as descriptive rather than intervenient due to the system's capacity for change, which is dependent on the connections. For example, in cases where the connections between components are fixed, the presence of open component edges may not be significant. Therefore, the position of feedback approaches is defined considering the capabilities in each of the decomposition aspects for enhancing changeability.

The last feedback type includes the analysis of connections together with service life information. The analysis of the architectural detail is shown in the dependency diagram. While feedback on connections is presented with a scale diagram from flexible to fixed, service life information is analyzed using a machine learning model, i.e., a random forest algorithm. The algorithm utilizes the service life data of each material from the dataset. If the material is present in the database, it provides the life expectancy to the dependency diagram. However, if the material is not found in the database, the algorithm searches for similar materials and proposes a prediction for the new material based on the predictive model. Taking into account the connections' feedback, the mechanism offers system feedback considering the following conditions:

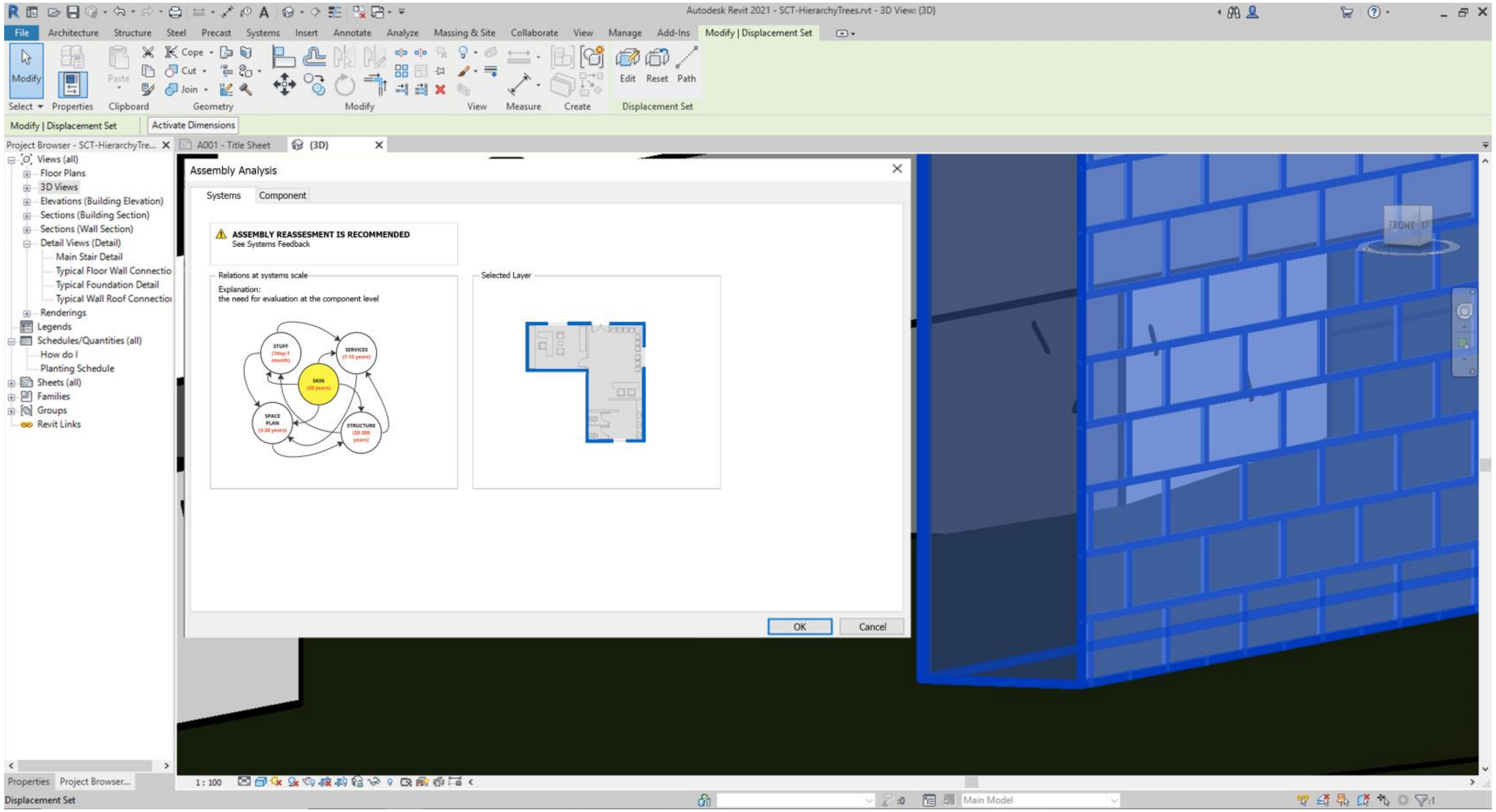
- **Condition 1.** If the connection is fixed and the service life of the hierarchical sub-material is lower than hierarchical up-materials in a tree diagram
- **Condition 2.** If the connection is flexible, the service life of the materials is not important
- **Condition 3.** If the connection is fixed and the service life of the hierarchical sub-material is higher than hierarchical up-materials in a tree diagram

The mechanism presents a final outcome for these conditions to assist the architect in the decision-making process. If Condition 1 is detected in the selected detail, the mechanism will alert the architect with a message stating "ASSEMBLY REASSESSMENT IS RECOMMENDED," accompanied by an explanation of the problem, such as "mismatch of service life of the materials". In the case of Condition 2, the result will be displayed as "ASSEMBLY IS VALIDATED," with an explanation stating "no problem is detected". For Condition 3, it will show a warning to the architect as “ASSEMBLY REASSESSMENT IS RECOMMENDED”, along with an explanation of the problem, indicating “*need of emergent maintenance”.* Although the last condition does not pose immediate problems considering the service life information of components, it still prompts the reassessment of assembly considering the emergent maintenance needs in components. Ultimately, the architect is expected to contemplate changing the material selection to ensure service life compatibility or adjusting the assembly detail with flexible connections. Accordingly, the proposed mechanism is anticipated to guide the architect`s decision-making process at the component scale. The next section outlines the definition of the user interface in the selected digital tool for such a mechanism, providing a clearer explanation of the guidance approach and its intervention level in the design process.

4.2.3.1 User interface of feedback mechanism

Building Information Modelling (BIM) stands as a widely utilized digital design tool in the construction industry, offering numerous applications and advantages. Despite its prevalence, however, current BIM tools fail to support the design process at the component level. Consequently, it was required for this research to adopt novel technologies that allow users to operate at the component scale. Among these, Digital twin emerges as a cutting-edge technology, providing 3D modeling across multiple levels of detail, yet continuing to evolve and advance in various directions. Within this framework, the development of user interfaces for the decision-making detailing strategy takes into account not only the present state of digital design tools but also anticipates their future evolution and enhancements.

In line with the previously outlined borderlines of the strategy, the user interface should provide feedback options at both systems and component scales. Configured within the Autodesk Revit tool, the system interface is illustrated in Figure 4.11. In the background, the user can see the selection highlighted in blue, which in this case is a brick masonry cavity wall. Within the newly opened window, called assembly analysis, two tabs are available; systems and component. Upon selecting the `system` tab, two boxes are presented as ‘systems analysis’ and ‘relations in system scale’. The systems analysis box shows the subsystem highlighted in blue in the plan of the building, identified as a wall in this case. Relations in the systems scale box show the relationship diagram at the systems scale. In the relationship diagram, yellow indicates the selected subsystem`s belonging layer and its service life information - here, representing a skin with a service life of 20 years. Positioned atop these boxes is a warning message for the architect, advising “ASSEMBLY REASSESSMENT IS RECOMMENDED”, with the explanation “*the need for evaluation at the component level”.*



Assembly Analysis

ASSEMBLY REASSESMENT IS RECOMMENDED
See Systems Feedback

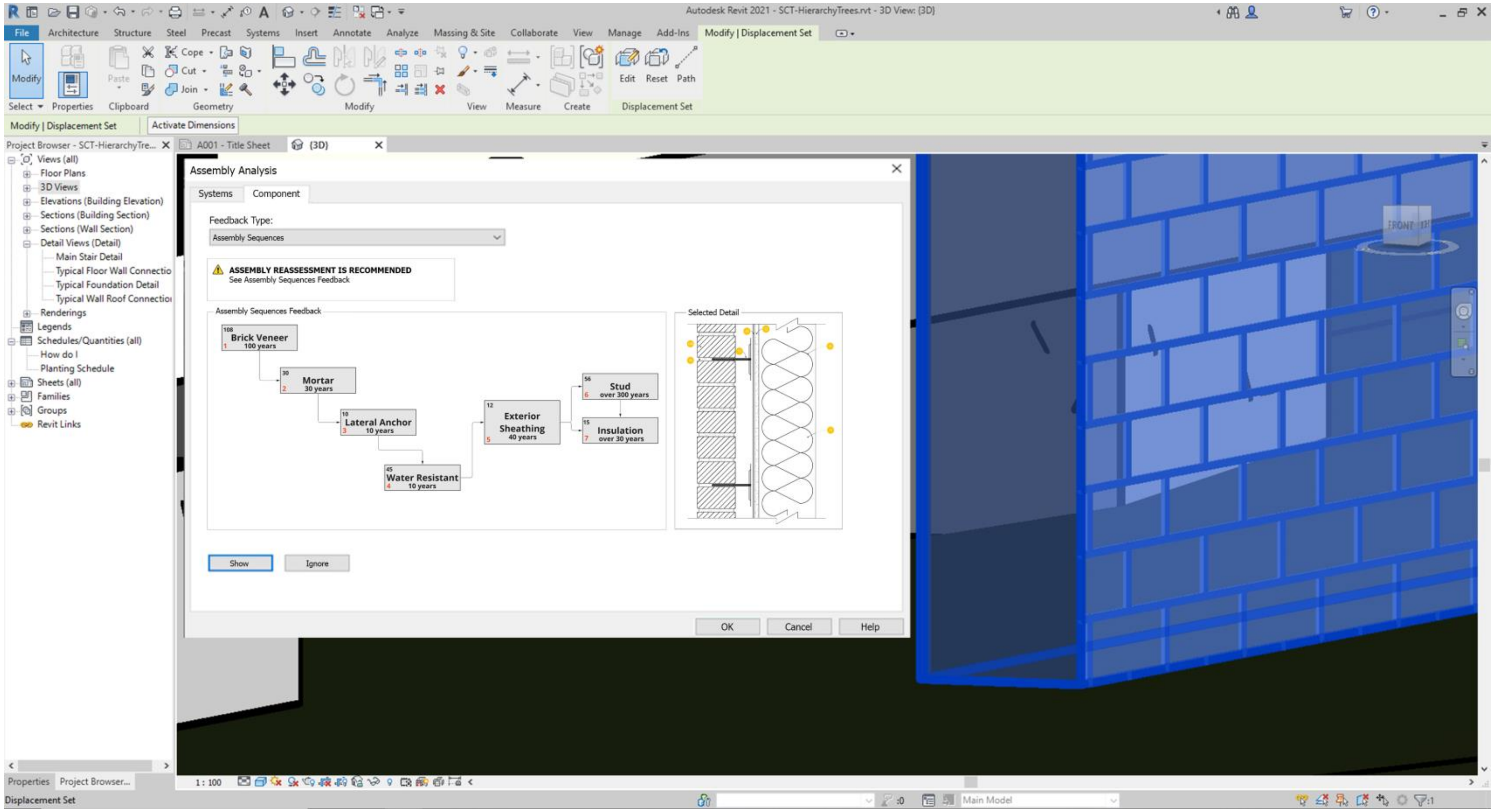
Relations at systems scale

Explanation:
the need for evaluation at the component level

Figure 4.11. User interface of feedback mechanism for systems analysis (developed by author)

When the user selects the component tab in the Assembly Analysis window, they must choose a type of feedback from the available options, which are assembly sequences, geometry of component edges, and connections & service life information. In the case of the assembly sequences feedback type, two boxes appear: the left one is dedicated to the assembly sequences feedback, while the right one presents the 2D drawing of the selected architectural detail (Figure 4.12). The assembly sequences feedback box displays a dependency diagram in the material box format. Architects can understand the assembly sequence of each material by evaluating both the dependency diagram and the drawing of the selected detail. The number of assembly sequences is located in the bottom left corner of the material box, highlighted in red font. Since assembly sequences are integrated into the system to inform architects about the assembly sequences, a warning sign is included with the label `ASSEMBLY REASSESSMENT IS RECOMMENDED`. At this stage, the architect can select the `Show` option for more details or choose to `Ignore` recommendation. If the architect selects the `Show` tab, a second window appears, providing further information.

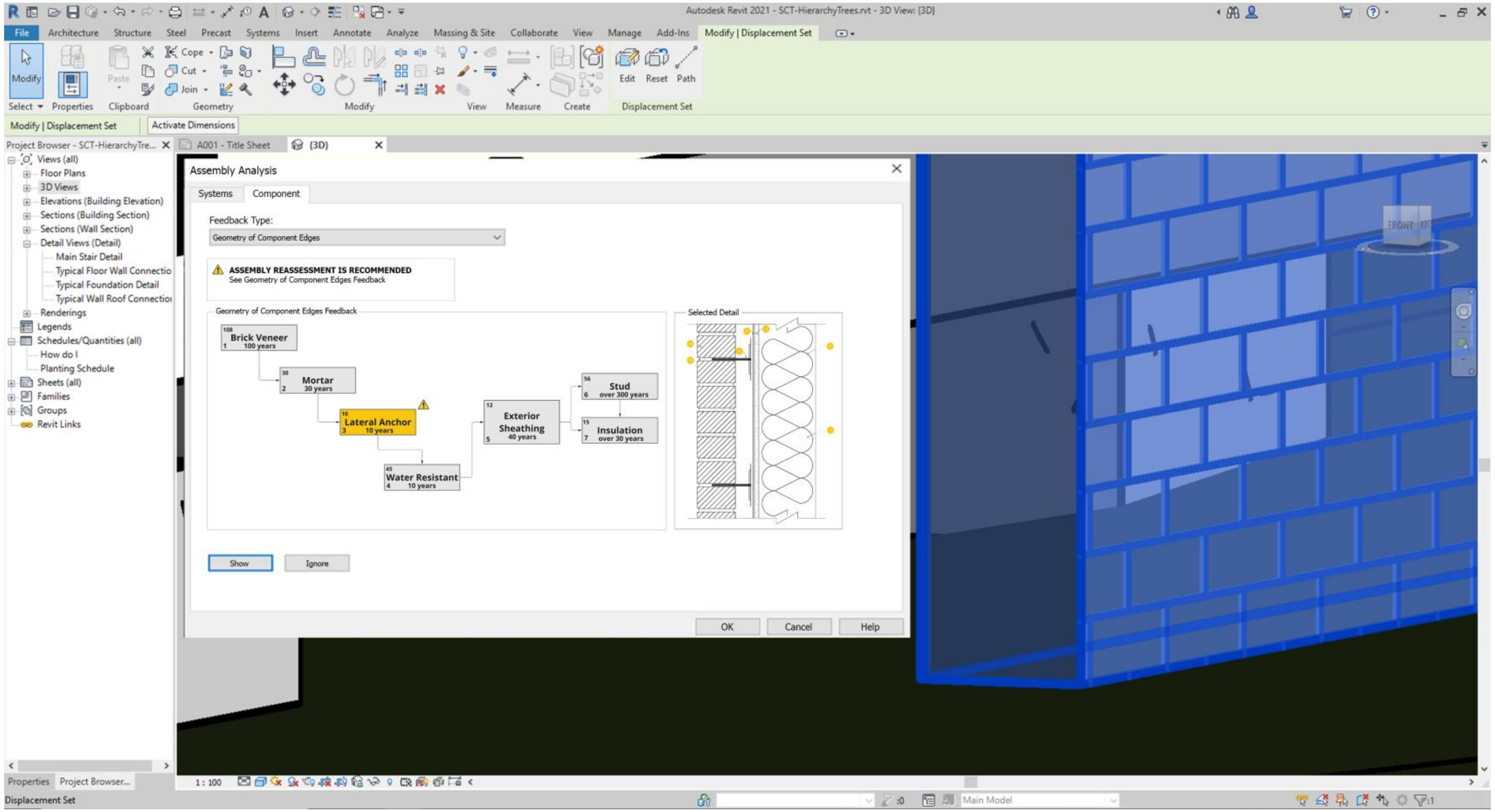
The same window arrangement is displayed when the architect chooses the geometry of component edges from the feedback type section, as shown in Figure 4.13. Here, the dependency diagram illustrates components that do not share open geometries with each other. Material boxes representing relatively more closed components are highlighted in yellow and outlined with a yellow exclamation mark. To illustrate, the lateral anchor is depicted in yellow since it lacks an open geometry with the neighboring components. If the architect selects the `Show` option, they can access additional information about the indicated component. Figure 4.14 illustrates the third option in feedback types, which pertains to connections and service life information. Upon selecting this option, a similar window interface is displayed with necessary adjustments in the dependency diagram. The dependency diagram adjusts to highlight potential assembly issues based on the analysis of the connections and service life information. Material boxes representing fixed connections and service life incompatibilities are marked in yellow with yellow exclamation marks. Similarly, the users select the `Show` option for further details about the connections and service life.



Feedback Type: Assembly Sequences

⚠ ASSEMBLY REASSESSMENT IS RECOMMENDED
See Assembly Sequences Feedback

Figure 4.12. User interface of feedback mechanism for assembly sequences (developed by author)



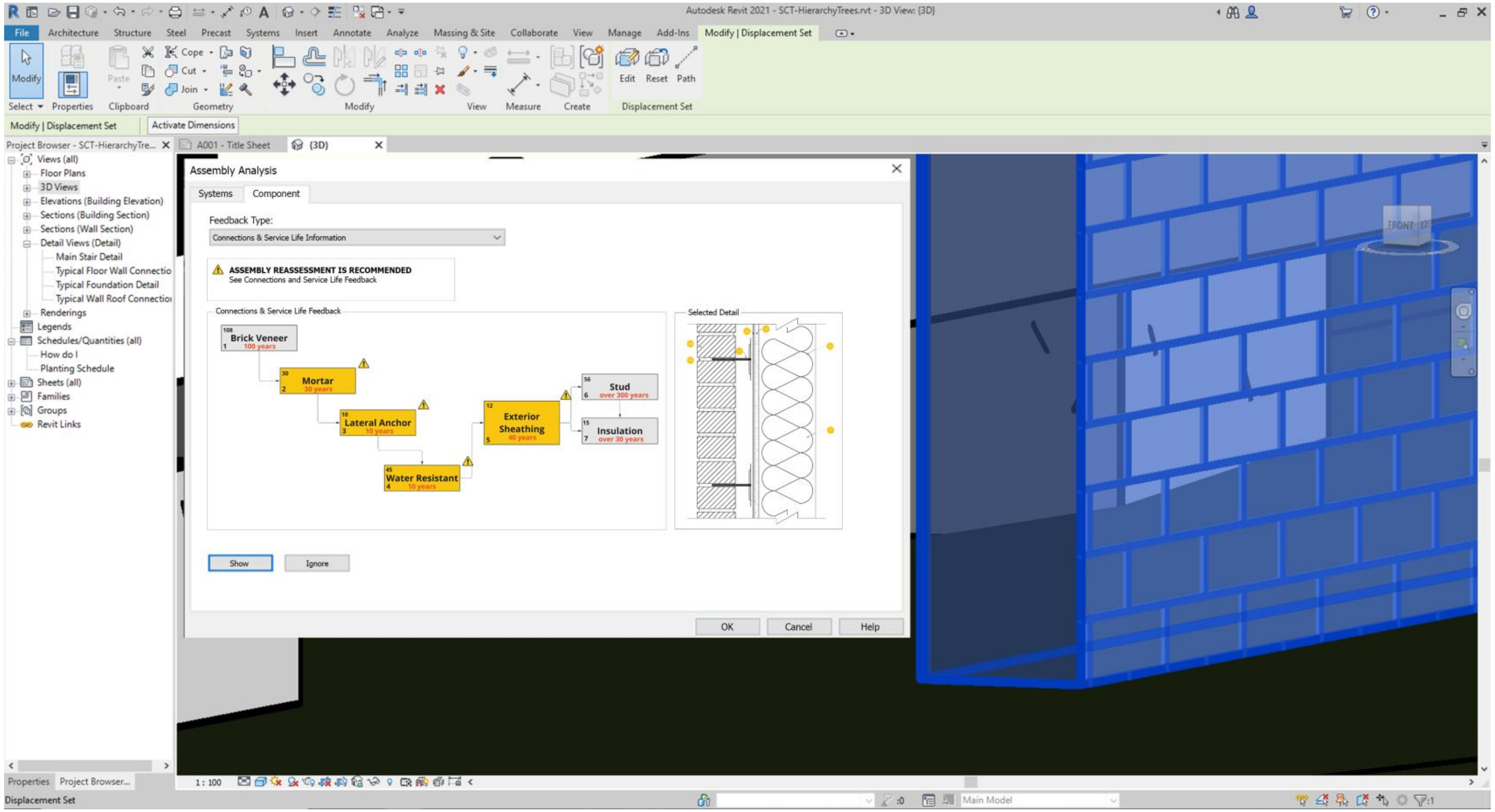
Autodesk Revit 2021 - SCT-HierarchyTrees.rvt - 3D View: {3D}

Assembly Analysis

Feedback Type: Geometry of Component Edges

⚠ **ASSEMBLY REASSESSMENT IS RECOMMENDED**
See Geometry of Component Edges Feedback

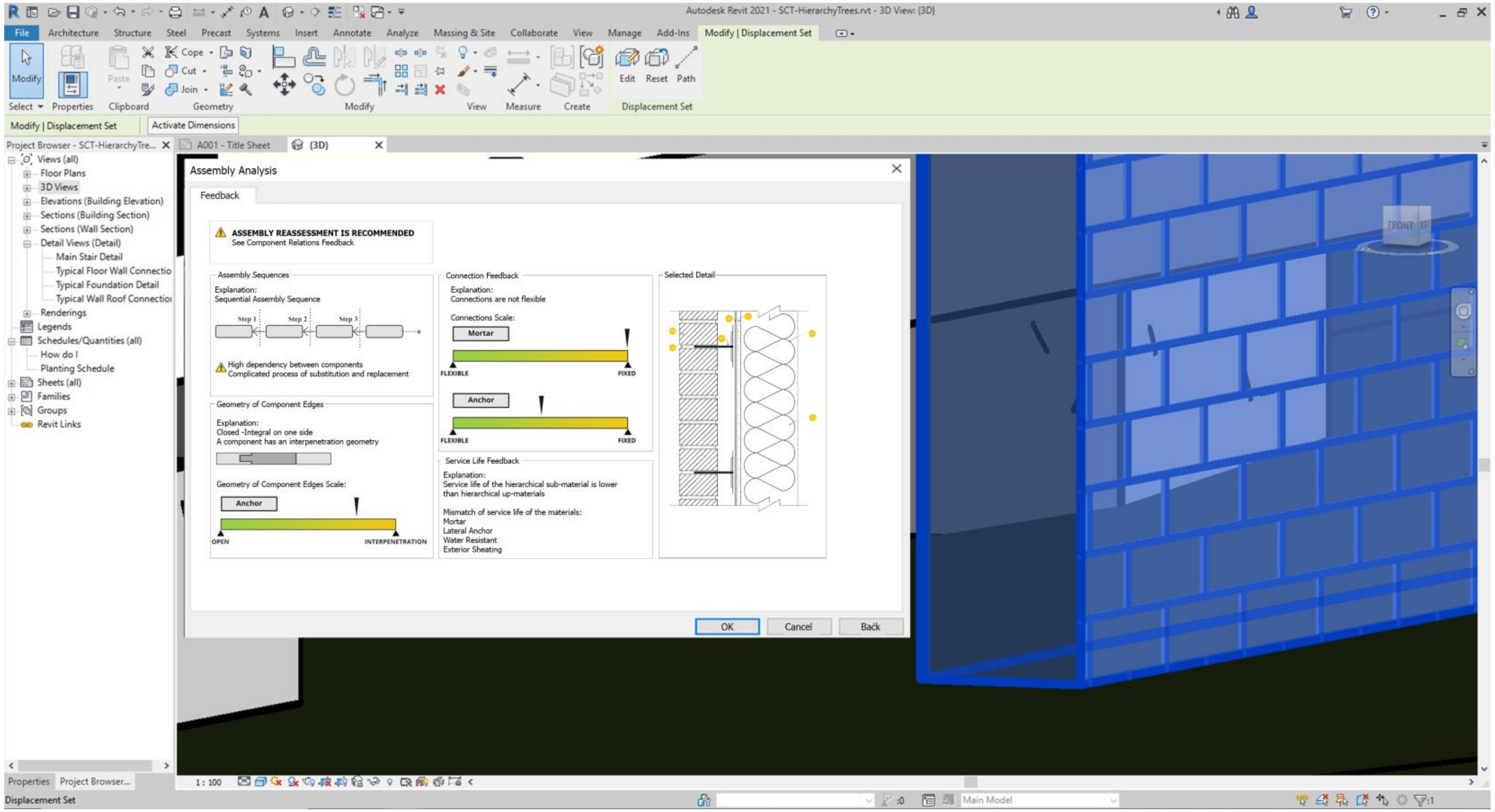
Figure 4.13. User interface of feedback mechanism for geometry of component edges (developed by the author)



Feedback Type: Connections & Service Life Information

⚠ **ASSEMBLY REASSESSMENT IS RECOMMENDED**
See Connections and Service Life Feedback

Figure 4.14. User interface of feedback mechanism for connections and service life information (developed by the author)



ASSEMBLY REASSESSMENT IS RECOMMENDED
See Component Relations Feedback

Assembly Sequences
Explanation:
Sequential Assembly Sequence

High dependency between components
Complicated process of substitution and replacement

Geometry of Component Edges
Explanation:
Closed -Integral on one side
A component has an interpenetration geometry

Geometry of Component Edges Scale:

Connection Feedback
Explanation:
Connections are not flexible

Connections Scale:

Service Life Feedback
Explanation:
Service life of the hierarchical sub-material is lower than hierarchical up-materials

Mismatch of service life of the materials:
Mortar
Lateral Anchor
Water Resistant
Exterior Sheating

Figure 4.15. User interface of feedback mechanism for feedback window (developed by the author)

When the architect selects the `Show` option in the analysis window, a feedback window opens in a new tab, as illustrated in Figure 4.15. At the top of the window, a warning sign `ASSEMBLY REASSESSMENT IS RECOMMENDED` is shown to guide the architect to the component relations feedback. Below it, four boxes display feedback on the decomposition aspects. Feedback on the decomposition aspects is presented in a single window, allowing the architect to understand the decomposition aspects both individually and holistically. The selected architectural detail is presented in a box to maintain the information flow from the analysis window to the feedback window.

In the assembly sequences box, the type of the assembly sequences is indicated with both written descriptions and diagrams. The architect is informed about the advantages and disadvantages of the selected assembly sequences. In the selected example, the analysis reveals that there is a sequential assembly sequence between components, indicating a high dependency between them. The architect is made aware that this type of assembly results in the complexity in the process of substitution and replacement of components.

The geometry of the component edges box provides an explanation of the indicated architectural detail from the analysis window. It shows a geometry analysis with simple explanations and a diagram. The analysis of the indicated architectural detail is further illustrated with a scale diagram depicting the range of open-interpenetration intervals. In the example, a lateral anchor is indicated with an exclamation mark in the previous screen since it has an interpenetration geometry with brick veneer. The problem is described with an explanation including the phrase "a closed-integral one side" along with a reference illustration from the literature review on the geometry of component edges. The scale diagram also shows the level of interpenetration of the component.

In the connection feedback box, the indicated architectural details are evaluated and explained simply. A scale ranging from flexible to fixed is displayed to present the difficulty level of connection in terms of disassembly. Mortar and anchor are highlighted with exclamation marks in the analysis windows since they are not flexible connections as indicated in the explanation section. While mortar is a fixed connection, the anchor is shown between flexible and fixed according to the flexible-fixed scale diagram. In the service life feedback box, the analysis of components in terms of service life is presented along with explanations, and any mismatches in service life among materials are listed. A mismatch in the service life is defined between the mortar, lateral anchor, water-resistant air barrier, and exterior sheathing in the selected architectural detail. This incompatibility is outlined by the explanation that `the service life of the hierarchical sub-material is lower than that of the hierarchical up-materials`. The user interface of the feedback mechanism for assembly analysis and feedback windows and corresponding tabs were also visualized with a user interface flowchart, which can be seen in Appendix B.

This study aimed to provide a component-oriented detailing strategy to assist the architects during the design phase in selecting building components and to guide building users and contractors during the use phase in establishing the maintenance and repair schedules. The preceding section urged upon the implementation of the proposal for the design phase and outlined the essential elements for its implementation. The following section focuses on the use phase scenario using a case study example and details the necessary infrastructure to construct the feedback mechanism during the use phase.

4.2.4 Utilization of the proposed strategy in the use phase

The feedback mechanism during the use phase aims to keep the building users or contractors informed about the predictive maintenance and repair needs. Since predictive maintenance is condition-based maintenance in which the systems of the building are monitored by sensors throughout the building`s life cycle, there is a necessity for a digital tool that enables the real-time connection between the building and design tools. In this study, digital twin technology is used to construct such a system. Digital twin technology supports stakeholders throughout the construction process, from designing new buildings to managing existing buildings. Considering the entire construction project timeline and the defined time limits of this study, the scope at this stage was decided to be limited to the existing building stock for the needs of renovation, refurbishment, and maintenance purposes.

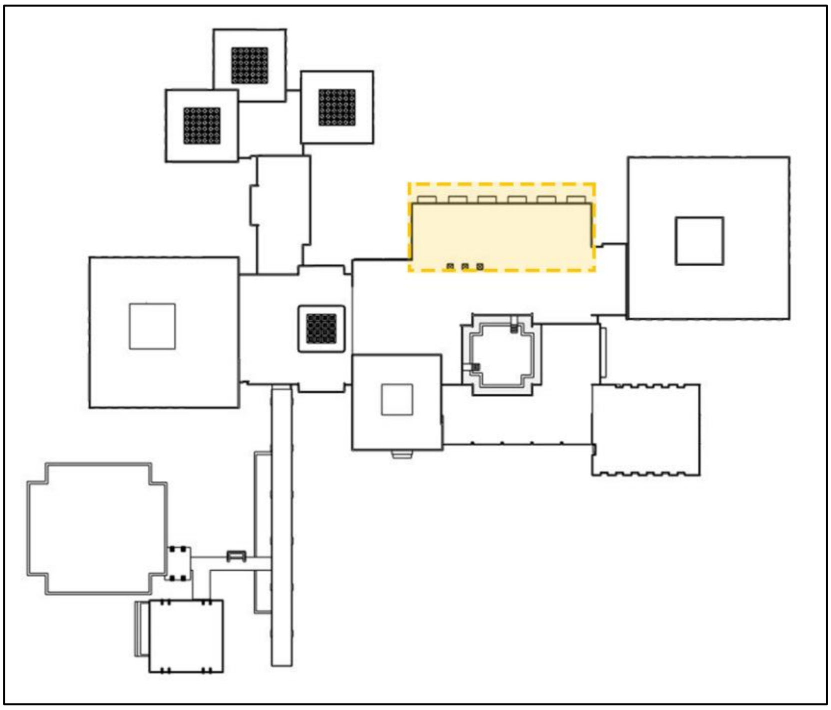


Figure 4.16. Selected classroom units in METU Faculty of Architecture

Middle East Technical University (METU) Faculty of Architecture building was selected as a case study. The building`s design by renowned architects Altuğ and Behruz Çinici in 1956 places it as an outstanding example of Turkish modernist architecture, providing rich architectural and historical context for the research. In recognition of its significance, the Getty Foundation awarded it in 2017, underlining its importance in the global heritage of modern architecture. However, considering the time that has passed since the construction of the building, it became vulnerable to the deterioration effects over time. The unique design features of the building require meticulous maintenance and repair scheduling, making it an ideal case study for discovering the application of cutting-edge technologies to sustain its value over time. The building includes diverse spaces serving various functions, from classrooms and design studios to administrative offices and social gathering spaces. Due to the scale of the building, classroom units were chosen to facilitate more manageable and effective research. The selected space includes many material combinations with reinforced concrete, autoclaved aerated concrete, steel, wood, and ceramic. Moreover, it has a small outdoor space which is important to understand the material deteriorations in interior and exterior conditions. In Figure 4.16, the classroom units are highlighted with yellow in the schematic plan of the METU Faculty of Architecture.

As a continuation of the feedback mechanism in the design phase, the system in use phase also depends on the previously explained mechanisms and datasets, including the assembly library and data sets for systems and components. Similarly, it uses the random forest algorithm to predict the maintenance needs of the components based on the data sets. However, existing datasets are required to include data from the sensor network for utilizing feedback mechanisms in the use phase. To achieve this objective, the sensor network is theoretically established based on an analysis of the classroom units. The following section informs about sensor selections with an analysis of classroom units.

4.2.4.1 Sensor selection

There are different kinds of sensors to monitor the building for a variety of objectives as described previously in Chapter 3. Considering the scope of this study, the focal point is on the building components and component relations. In that sense, sensor selections were done considering the factors affecting the service life of the components. Firstly, water is a significant factor that can cause deterioration of building materials over time when exposed for extended periods. Upon analyzing the case, potential areas susceptible to water-based deterioration were identified. The heating system poses a risk of water leaks in the future. Similarly, moisture accumulation can be observed in the exterior walls due to their role as interfaces between the interior and exterior spaces, especially influenced by variations in thermal conditions. Accordingly, a water sensor was selected to anticipate potential leaks in the interior surfaces of walls. Similarly, moisture monitoring sensors were chosen to detect moisture in the exterior walls. Furthermore, corrosion is another prominent factor affecting the service life of the materials. Corrosion is observed if there is an oxidization in metal surfaces. Since concrete walls in this case may have corrosion over time, corrosion sensors are preferred to detect the potential corrosion areas in the walls.

Figure 4.17. Sensor locations in classroom units (source: author)

Apart from the sensors in component scale, threshold and mechanical sensors were chosen to examine the wear condition of the doors and windows by counting the number of open-close situations. The potential positions for the selected sensors are shown in Figure 4.17. After the establishment of the sensor network in the selected case, it is anticipated that existing data sets will be updated with the operational data extracted from the sensor network. By implementing this approach, the proposed strategy not only assists the pre-management of component relations across multiple levels, but also facilitates the control over unexpected circumstances at component scales, thereby prolonging the building`s life cycle.

4.2.4.2 Integration with digital twin

As the final stage of a component-oriented decision-making strategy, the feedback mechanism in the use phase requires a platform that both uses existing data and updates the system with real-time data. This strategy proposes the use of digital twin-based tools to construct such a platform. This stage aims to provide access to multiple users in the construction industry, including architects, contractors, and building users. Digital twin architecture relies on wireless sensor networks and data analytics. In this study, the digital twin architecture is constructed based on the study of Khajavi et al. (2019).

Figure 4.18 outlines the theoretical construction of a digital twin for the METU Faculty of Architecture. Data models that are generated during the utilization of the feedback mechanism in the design phase constitute the virtual model, comprising 2D Drawing files, 3D models, and systems and component relations datasets. Sensors such as water sensors, moisture sensors, corrosion sensors, and threshold and mechanical sensors are selected to establish the sensor network.

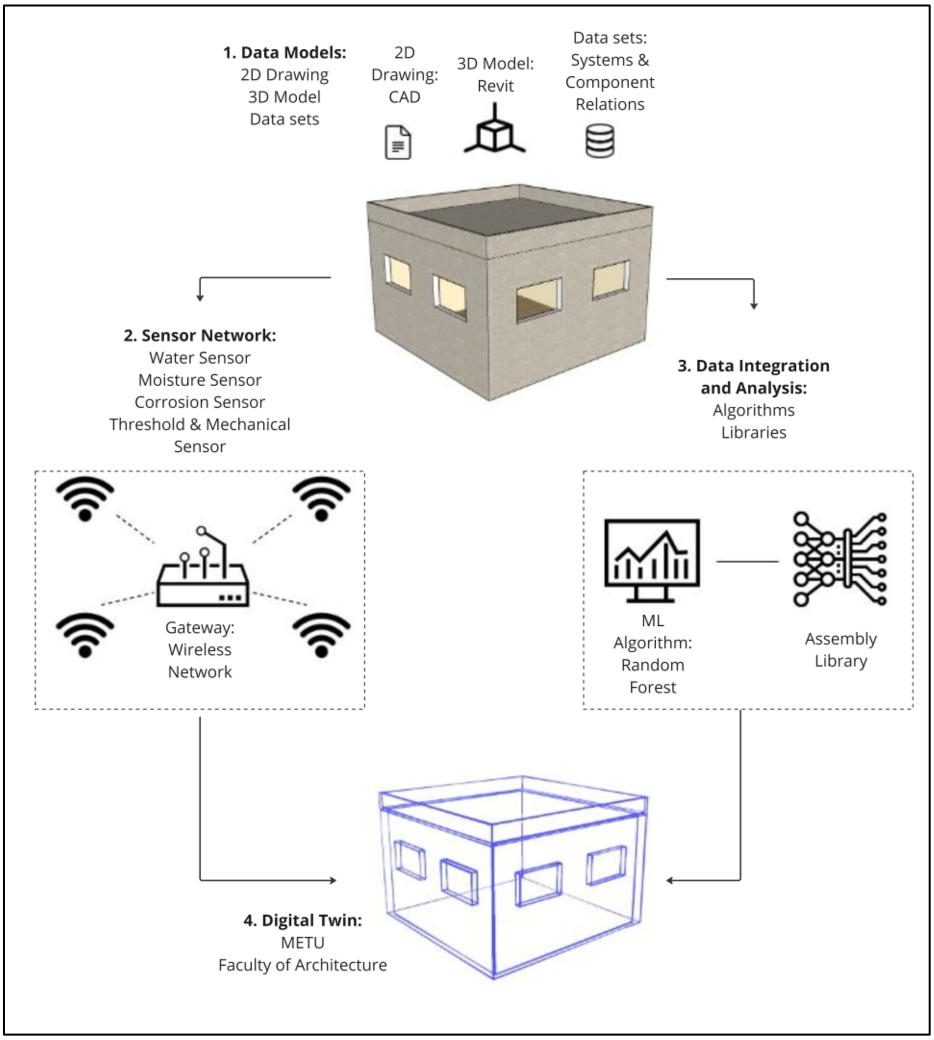


Figure 4.18. Theoretical construction of Digital Twin for the selected case (developed by the author)

This network provides data to be used to develop maintenance and repair schedules. At gateway nodes, operational data which are gathered from sensors is merged by using a wireless network. In the third step, data is integrated and analyzed by using machine learning algorithms and dataset libraries. Here, it uses the base of the feedback mechanism in the design phase, including the random forest algorithm and assembly library. Analyzed data yields insights into the physical twin. The virtual model of METU Faculty of Architecture can provide feedback to the physical model about the maintenance and repair schedules using operational data as well as the assembly analysis of the faculty using the design phase data.

CHAPTER 5

CONCLUSION

This research has delved into the development of an architectural detailing strategy that focuses on building components and implements it with decomposition aspects. Addressing the drawbacks of the non-adaptable building structures in current practices, strategies fostering adaptability and transformability in buildings were explored. It was revealed that current design practices do not support future adaptability of buildings, and fail to consider the time factor in the design process. Additionally, the construction industry typically neglects the role of architectural details in the assembly process, which holds a huge potential to lengthen the building life cycle. While other industries prioritize details to provide a prolonged beneficial life cycle for products, the construction sector focuses on life cycle assessment only as an energy-saving measure. To this end, a component-oriented detailing strategy was developed, which establishes feedback support for the design process from the early design to the use phase. To assess how such a strategy could facilitate the management of a buildings' beneficial life cycle with control over the components, an architectural detailing example, and a case study were studied. This strategy not only develops the initial considerations of architectural detailing in the design process but also improves the change management in building components when there is a need for disassembly.

Responding to the existing gaps in the literature, this thesis has two main contributions. Firstly, it proposes an analysis method for architectural details in the design process, focusing on decomposition aspects. This approach will offer guidance to architects during the early design phase, encouraging consideration of component changeability. Secondly, it provides a mechanism for controlling components during the use phase of buildings. This will help building managers or occupants to facilitate maintenance and repair needs in a timely and efficient manner.

This study conducted a comprehensive analysis of buildings, examining them from systems to component scales. Each scale yielded valuable information to support component changeability, considering various factors related to component properties. Dependency analysis conducted across multiple scales revealed hidden relationships among components, which are key considerations for creating adaptable buildings. By highlighting these unseen relationships, architects can consider component combinations in architectural detailing through considering multiple aspects. While the design process typically anticipates the usage of buildings after construction, it's important to recognize that buildings may undergo unforeseen changes by their users. The proposed strategy in this research aims to facilitate control over buildings for both planned and unplanned changes throughout the use phase. Overall, by embracing this approach, architects, engineers, and stakeholders in the construction industry can expect to achieve several significant features for their design throughout multiple stages of the building lifecycle.

In addition to the main conclusions, this research may provide a platform for encouraging the stakeholders of the construction industry for the utilization of cutting-edge technologies, i.e., it may pave the path for the transition from BIM to digital twin technology. By extending the life cycle of building material assemblies, the awareness of materials’ varying lifecycles can be increased. This may lead to improved quality management in the construction sector, as it can affect the development of tailor-made assembly properties to meet user expectations. Furthermore, it can drive advancements in durability through planned maintenance and repair schedules, potentially resulting in the development of more environmentally friendly construction practices.

As this study supports both inductive and deductive architectural detailing processes through the proposed strategy, it may alter the role of architects in these processes. Enhancing architects' understanding of architectural detailing and their involvement in detail selection can help resolve discrepancies between architects and architectural engineers. Just as architects were once master builders, today's architects can reclaim their influence through the power of digital design tools using the proposed strategy.

Moreover, the proposal can contribute to the implementation of lean design principles in the construction stage by diminishing design-based problems. It supports architects by giving them control over architectural detailing from the early design phases and enables them to evaluate aspects related to architectural detailing that may be beyond their usual expertise.

The proposed strategy also contributes to the resilience of building structures against various external factors and supports long-term sustainability goals. Using materials till the end of their lifecycles and efficient management of change needs in buildings eventually contributes to a more sustainable built environment and circular thinking. It opens a promising pathway toward reaching sustainable building practices by providing adaptability without compromising the durability of building materials. Moreover, it has the potential to influence the development of construction regulations considering assembly changes throughout the building life cycle.

This research highlighted the importance of balancing building changeability with preserving building materials. Providing feedback in the design process may open avenues for architects and designers to create more flexible and transformable structures that can evolve over time. It may inspire new ideas and practices in the field by promoting adaptability in architecture and may foster the construction of buildings that can better respond to the varying needs of occupants.

5.1 Revisiting research questions

The main research question guiding this study is: *How can we support architects to control the component relations in the early design phase for effective operation and maintenance in the use phase of the building life cycle?*

To answer the main research question, a component-oriented detailing strategy was developed to guide architects in controlling the component relations in the early design phase and to guide the building users and contractors in scheduling the maintenance needs in the use phase of the building life cycle. This strategy aims to ensure effective design and operation by assisting architects and building users in the building life cycle. To delve deeper into the proposed strategy, the following sub-questions were addressed:

What are the main problems in the conventional design process, that result in excessive energy usage and construction waste?

In Chapter 1 and Chapter 2, the study examined the effect of using time factor in the design process. Design processes in cross-industries were studied to identify possible solutions and to detect existing malpractices in the construction industry. Accordingly, it was found that there is a lack of information in the early design phase, architectural detailing understanding is not developed, circular design is not well handled within the life cycle of buildings, and the life cycle assessment studies do not support the full design process due to the uncertainty of boundary definition.

What is the functioning mechanism of the building system? How can we decompose a building to understand the component relations? Which factors are important in evaluating architectural detail?

After the main implications from the cross-industries and addressing the problems in the building design process, it is realized that buildings should be treated as systems and each component should be evaluated as a part of the system. For that reason, the study studied buildings on multiple scales and developed an analysis from the systems level to the component level. To understand the unrevealed relations between the components, several methodologies were examined, and the Design Structure Matrix was selected, as described in Chapter 3. According to the literature findings, buildings can be decomposed as levels and layers on a systems scale. In component scale, architectural detailing can be classified based on the component relations called decomposition aspects. In the evaluation of the architectural details, the layer model was found to be significant at the systems scale; and assembly sequences, the geometry of component edges, connections, and service life information were found to be determinant factors in the component scale.

How does the feedback mechanism work with the data sets? How can data sets be developed thinking the service life information and connections?

As outlined in Chapter 4, the feedback mechanisms were tailored to address both the early design and use phases of the building lifecycle. In the early design phase, the feedback mechanism included datasets related to systems and component relations. The systems relations data set includes information about the layer model and corresponding service life information. The component relations data set consists of the material descriptions, service life information, and properties related to decomposition aspects. The feedback mechanisms in the early design phase were operationalized based on the assembly library mechanism's functioning principle.

Which program will be used while guiding the architects? What interface is applicable within the feedback mechanism?

Feedback mechanisms were developed to guide the stakeholders of construction in multiple stages of the building lifecycle. In the early stages of the design process, architects are guided by the digital design tool Revit. The designed interface was configured by using the interface of the Revit program. In the interface, architects can obtain information related to the selected architectural detail over a digital window called assembly analysis. Assembly analysis provided different tabs for decomposition aspects at systems and component scales. At the systems scale, the user interface of assembly analysis includes one window for the analysis of systems scale and feedback. At the component scale, the user interface of assembly analysis diversified with digital tool interfaces based on the decomposition aspects including the assembly sequences, the geometry of product edges, connections, and service life information. When the user selects to show the analysis, the feedback window opens to show the analysis of the aforementioned decomposition aspects.

How does the feedback mechanism work in the use phase? What are the related components to construct real-time data transfer?

Feedback mechanisms in the use phase of the buildings were aimed to guide the building users and contractors about the maintenance and repair needs of the buildings and help them with any other unplanned changes in building components. The feedback mechanism in the use phase was developed with the digital twin tools. To construct a digital twin, the necessary infrastructure was researched. To that end, it was found that the wireless sensor network and data analytics are necessary to construct real-time data transfer. Existing data sets were thought to be updated with the sensor network. It was assumed that the virtual model comprising 2D Drawing files, and 3D models were developed with the updated data sets. This data was designated to be analyzed using the assembly library mechanism with the machine learning algorithms. As a case, classroom units in an educational facility were chosen and evaluated with prospective sensor networks. The digital twin architecture was constructed using this case as an example.

5.2 Limitations and challenges

While this study contributes to the field with various insights into the future of adaptable buildings, it is necessary to recognize its limitations. These limitations underline the topics where the research has certain constraints. With the discussion over these limitations, a comprehensive understanding of the scope may be reached and the research may address the potential development points for the future.

Firstly, this research provides a component-oriented strategy that utilizes the existing digital design tools, acknowledging the potential for future advancements in these tools. As digital design technologies continue to evolve, it is anticipated that digital design tools increase the level of detail in their interfaces, and the proposed strategy can provide more insights into the decision-making process to the architects. Secondly, the proposed strategy requires the service life information of the materials to support the component data sets. Literature findings showed that there is no consensus on the exact numbers for the service life information of the materials. To build a stronger evaluation in the assessment of architectural detailing considering the service life compatibility of the components, it is important to reach the internationally accepted database of the service life information. Thirdly, the decomposition aspects that are used to analyze the architectural details in this study could be developed since there is potential for further development to examine the latest advancements in architectural detailing. Considering the time constraints, the study was limited to existing decomposition aspects as framed in the literature.

Lastly, this study uses an existing building example to show the digital twin implementation in the use phase. It would have been more informative and could have broadened the study`s scope if the selected building example had covered the processes in both the early design and use phases. It could have offered deeper insights into the realization of the project from the early design phase to the use phase. Moreover, the selected example for the digital twin implementation is limited to a section of a building. It would offer a more comprehensive understanding if the selected case had encompassed the entire building.

5.3 Recommendations for future work

Concluding the study, there are several promising areas for future research and development. Firstly, while this research framework presented a decision-making process in architectural detailing, future work could focus on implementing this strategy in real-world architectural projects, starting from the selection of a building to be constructed. By doing so, the effectiveness and implementation of the proposed strategy can be thoroughly evaluated in real-world scenarios. Moreover, the user interface proposed in this study establishes a base for developing architectural plug-ins that can further enhance the feedback mechanisms. Incorporating feedback from users would provide valuable insights for refining and developing the feedback systems, ensuring they meet the industry’s needs and user requirements.

In addition, as the proposed strategy offers a more comprehensive evaluation of architectural detailing considering the capabilities of current digital design tools, future studies could focus on the ontological relationships between building components at the component scale, serving as a base for IFC developments in digital design tools. Furthermore, future work could explore the integration of digital twin technology to encompass entire buildings rather than specific parts. This broader approach would enhance our understanding of how digital twins can be effectively implemented across various architectural contexts and throughout the entire lifecycle of a building.

Additionally, this study did not intend to integrate material passports into the methodology of the study since it proposes a strategy that includes information about not only the material qualities but also the physical relationships and dependencies. Further research is advised to search for the methods for the integration with the material passports for following the circular economy principles. Moreover, future study is advised to widen the decomposition aspects of this study. Merging the recent advancements in architectural detailing and materials science could bring about more accurate evaluations of building components by dedicating more resources. Lastly, sustaining the building's transformability can be supported by the integration of such thinking in architectural education. Enhancing the architect`s role in the design process and changing their involvement in material science would be a valuable direction for future research efforts.

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APPENDICES

A. Literature review list

Table A.1: A literature review of decomposition approaches with the categorization of the aims

Authors	**Aim**	**Theory**	**Place**	**Field**	**Categorization of the aims***		
					En.	**S.**	**Ec.**
Habraken (1961)	Authorization of the user during the building process	Support & Infill	Netherlands	Design		x	x
The Century Housing System (late 60s)	Extension of the building`s longevity by sequencing the assembly of components		Japan	Design	x		x
Rush (1986)	Categorization of the building systems	Building Systems Integration Theory	USA	Mechanical			x
Duffy (1990)	Responding to the rate of change in buildings	Layers of time	United Kingdom	Design	x		x
Brand (1994)	Measurement of the building with the relations of building components and change needs	Shearing Layers	USA	Design	x	x	x

Pimmler & Eppinger (1994)	Analysis of relations in complex systems		USA	Management			x
Sosa, Eppinger, & Rowles (2000)	Classification of the interactions in a system		USA	Management			x
Slaughter (2001)	Analysis of the characteristics of changes in the built environment		USA	Design	x		x
Friedman (2001)	Increase in the understanding of the workings of a system		Canada	Management		x	
Leupen (2002)	Definition of permanent and changeable spaces	Frame and Generic Space	Netherlands	Design	x	x	x
Bachman (2003)	Development of systematic thinking in the building design process		USA	Design	x		x
Zimmann, O`Brien, Hargrave & Morrell (2016)	Exploration of the circular economy principles and their applications		United Kingdom	Environmental	x		x
Schmidt & Austin (2016)	Evaluation of dependency between building layers		United Kingdom	Design	x	x	x

(*) Categorization of the aims: En (Environmental), S (Social), Ec (Economical)

B. Flowchart of user interfaces

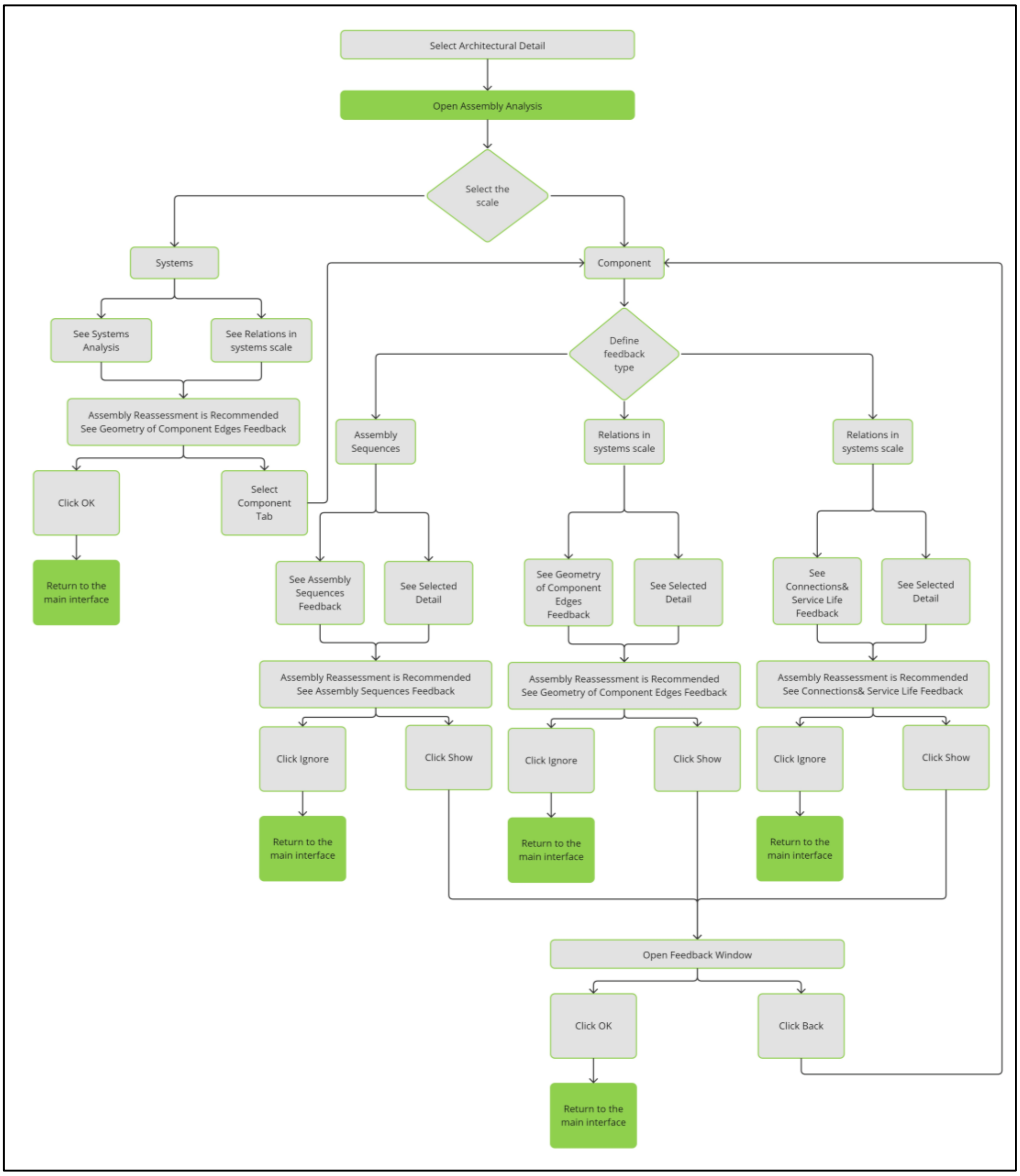

Figure B.1. Flowchart of user interfaces in digital tools

CURRICULUM VITAE

Surname, Name: Çankaya Topak, Sıla

EDUCATION

Degree	**Institution**	**Year of Graduation**
MS	Bilkent University Interior Architecture and Environmental Design	2016
BS	Middle East Technical University Architecture	2013

ACADEMIC EXPERIENCE

Enrollment	**Institution**	**Year**
Part-time Instructor	Çankaya University, Turkey	2023- Present
Visiting Scholar	The Pennsylvania State University United States of America	2021-2022
Full-time Instructor	Çankaya University, Turkey	2016 -2021
Assistant Student	Bilkent University, Turkey	2014 -2016
Architect	Semafor Architectural Office	2013- 2014

RESEARCH AREAS

Data-Driven Architecture, Building Information Modelling, Digital Twin, Process Planning, Architectural Acoustics.

PUBLICATIONS

Journal Articles

Çankaya Topak, S. & Yılmazer, S. (2022). *A comparative study on indoor soundscape assessment via a mixed method: a case of the high school environment.* Applied Acoustics (SCIE), 189, pp. 108554. https://doi.org/10.1016/j.apacoust.2021.108554

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Conference Proceedings & Presentations

Çankaya Topak, S., Gönenç Sorguç, A., & Messner, J. (2022, May 13). *A component-oriented strategy for building digital design using a product architecture.* International Conference on Challenges for the Next Generation Built Environment, Bologna, Italy.

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Funded Projects

Önge, M. (coordinator), Çavdar, R. Ç. (researcher), **Çankaya Topak, S. (researcher)**, "A Post-Covid-19 Teaching Model Proposal for Architectural Representation Methods" Çankaya University Scientific Research Projects Commission, Project No: MF.20.003, 2020- 2022.

AWARDS AND HONORS

The Scientific and Technological Research Council of Turkey (TÜBİTAK) International Scientific Publication Incentive Award	December 2023
The Scientific and Technological Research Council of Turkey (TÜBİTAK) International Research Fellowship Program Scholarship for PhD Students	2021-2022
Gesellschaft für Internationale Zusammenarbeit (GIZ) Full Scholarship for Summer School on Energy Efficiency	July 2018
The Scientific and Technological Research Council of Turkey (TÜBİTAK) International Scientific Meetings Fellowship Program Scholarship	2016
Bilkent University Full Scholarship (Master Education)	2014-2016
Ministry of Education Fırıncılar Education Campus Architectural Competition, 3rd Prize	February 2014
Middle East Technical University, Department of Architecture Dean’s Honor List	June 2013
Mimed Architecture Students Awards Jury’s Special Award	2012
Solar Decathlon China 2013 One of the 20 finalists (w/Team Turkey)	2012