Design for disassembly as an alternative sustainable construction approach to life-cycle-design of concrete buildings

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Declaration

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly with due reference to the literature and acknowledgement of collaborative research and discussions.

The work was done under the guidance of Professor Alexander Furche at the Institute of design and construction, Leibniz University Hanover.

Wasim R. Salama

Dedication

I dedicate this book to my mother Feryal, my father Rida, my wife Rose, my children Odai and Yousuf and to the spirit of my grandmother Nasrah. Their prayer and support along the way were the cause of this success.

Acknowledgment

First of all, I would like to thank God (Allah sobhanah), many thanks also to my supervisor Professor Alexander Furche for the continuous support and follow-up. Special thanks from the bottom of my heart to my wife Rose for all the support and patience she showed during the period of my study. I should also acknowledge the time and valuable directions I got from Dr. Elma Durmisevic. Thanks for my friend Dr. Mahmoud Jahjouh who was more than a brother during my stay in Germany. I am grateful to all friends and colleagues who helped me whether by consultation or other support.

This study also would have been impossible without the support of the German Academic Exchange Service (DAAD) which supports ambitious young researchers from all over the world to reach their academic goals.

Abstract

Concrete buildings suffer from a disconcerting end-of-life scenario that is dominating by the demolition processes. The demolition not only prevents from reuse of the building elements and components but also contaminates the environment by dust, noise and solid waste. It also causes several kinds of disturbance to the site and its surroundings. This in addition to other non-preferable aspects is caused due to the ignorance of the life-cycle design of concrete buildings. While steel and timber buildings can be easily disassembled and removed, concrete buildings - especially those made from cast-in-situ concrete - have no options except demolition. To move concrete buildings to a higher level of construction sustainability and architectural adaptability the construction of concrete buildings should consider the design for disassembly (DfD). In this case concrete building elements and components can be disassembled and recovered by reuse or recycled or can be changed or replaced. Many benefits could be obtained from designing buildings for disassembly. It has been approved that DfD provides the buildings with high transformation capacity that leads to a higher sustainability; it also turns the linear life-cycle model of buildings to a more cyclic one. A review of the previous successful attempts to dismantle concrete buildings - and reuse some of its elements - has shown that despite the complexity of the work and a percentage of material loss precast concrete systems still have promising aspects.

This study aims to consider DfD of concrete buildings from an architectural construction point of view. Through exploration and revision of the current issues related to the concrete technologies and their role in building, assembly and disassembly as well as DfD aspects, theories and guidelines. Based on that a comprehensive analysis of the current used architectural precast systems and elements has been carried out. The results of the analysis have been utilized to identify areas of weakness that may cause loss of time or material through the assembly and disassembly processes. The enclosure system of the concrete buildings then has been chosen for development of systems to have high disassembly potential by introducing some concepts and improvements. These developments have led to façade systems that support reuse, change, replacement, update and adaptability. The developed façade systems have been evaluated and proved to be sustainable with regard to their environmental impact by achieving high values for seventeen determining factors of eight DfD aspects.

A part of the study has been didicated to the application and modeling through a case study. This case study has been explored analyzed and developed to guarantee the successful implementiation of the developed system in buildings and to provide a complete picture regarding their application.

At the end, the study was able to reposition the concrete buildings in the context of cradle-to-cradle design, analyzes their elements and systems with regard to their transformation capacity and to provide concepts of development that move DfD of concrete buildings from theories to practice.

Keywords

concrete buildings; design for disassembly; precast concrete systems; reuse concrete; buildings lifecycle; transformation capacity; disassembly; demountable systems; technical composition; concrete facades

Kurzfassung

Stahlbetonkonstruktionen leiden unter einem umweltunfreundlichen Ende des Lebenszyklus, welches von Abbruchprozessen dominiert wird. Der Abbruch verhindert nicht nur die Wiederverwendung von Bauteilen und Komponenten, die in vielen Fällen noch für längere Zeit tragfähig und verwendbar wären, sondern belastet auch die Umwelt durch Staub, Lärm und feste Abfälle. Darüber hinaus verursachen Abbruchprozesse verschiedene Arten von Störungen am Standort und dessen Umgebung. Während Stahl- und Holzbauten leicht zerlegt und transloziert werden können, besteht für Stahlbetonbauten, besonders aus Ortbeton, neben dem Abbruch keine Alternative.

Um Stahlbetonkonstruktionen in dieser Hinsicht auf ein besseres Niveau zu bringen, indem Bauteile und Komponenten aus Beton wiederverwendet werden können, sollten Stahlbetonkonstruktionen unter anderem für die Demontage, das so genannte Design for Dissassenbly (DfD), entworfen werden. Mithilfe von DfD können unter Aspekten der Nachhaltigkeit eine Reihe weiterer Vorteile erreicht werden. Crowther weist nach, dass sich das Lebenszyklusmodell der Gebäude von einem linearen zu einem zyklischren wandeln lässt. Eine Literaturrecherche bisheriger Versuche, Stahlbetonbauten zu demontieren und einige ihrer Elemente wiederzuverwenden, zeigt, dass Betonfertigteile trotz der Komplexität der Arbeit und eines prozentualen Materialverlustes , großes Potential im Hinblick auf DfD besitzen.

Ziel dieser Studie ist, es Konzepte für die Demontage von Stahlbetongebäuden vom Standpunkt der Konstruktion aus zu erarbeiten und diese vor dem Hintergrund aktueller Fragen der Betontechnologie zu diskutieren. Darüber hinaus werden die Bedeutung für Bau,Montage und Demontage, sowie DfD Aspekte, Theorien und Richtlinien betrachtet. Darauf aufbauend wurde eine umfassende Analyse der derzeit verwendeten Fertigteilsysteme und -elemente durchgeführt.

Die Ergebnisse der Analyse wurden verwendet, um Schwachstellen zu identifizieren, die einen Zeit- oder Materialverlust durch die Montage - und Demontageprozesse verursachen können. Für die Entwicklung von Systemen mit hohem Demontagepotential wurde die Hülle von Stahlbetonbauten ausgewählt, wobei einige Entwicklungen und Verbesserungen eingeführt wurden. Am Ende wurde eine Fallstudie erarbeitet, um das erfolgreiche Durchführen des entwickelten Systems an Gebäuden zu verifizieren und ein vollständiges Bild zu liefern.

Die Studie war in der Lage, die Stahlbetonkonstruktionen im Rahmen von Cradle-to-Cradle-Design zu positionieren, ihre Elemente und Systeme hinsichtlich ihrer Transformationskapazität zu analysieren und Konzepte der Entwicklung zu liefern, die DfD von Betonbauten in Bezug auf ihre Elemente und Komponenten aus den theoretischen Konzepten in die Praxis bringen.

- **Schlüsselwörter:**

Design für die Demontage; Betonfertigteile; Gebäudelebenszyklus, Technische Zusammensetzung; Betonfassaden; Beton wiederverwerten

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List of abbreviations

DfD	Design for disassembly
CMU	Concrete Masonry Units
AAC	Autoclaved Aerated Concrete
ICF	Insulated Concrete formwork
PC	Polycarbonate
SIPs	Structural Insulated Sandwich Panel
MDF	Macro Defect Free
DSP	Dense Silica Particle
CRC	Compact Reinforced Composite
PCA	Portland Cement Association
PCI	Precast/prestressed concrete institute
FRC	Fiber Reinforced Concrete
NU ties	Truss shaped glass fiber reinforced polymer ties
HRM	Heating and Rubbing Method
TC	Transformation Capacity
LEED	Leadership in Energy and Environmental Design
DNGB	German Sustainable Building Council
U.S.	United States
PRESSS	precast seismic structural system
CBF	Continuous Basalt Fiber
FPA	Façade Panel Anchor System
NPCAA	National Precast Concrete Association of Australia
DIN	German Institute for Standardization
APC	Architectural precast concrete
GRP	Glass Reinforced Plastic

Introduction

Background

It became clear that building and construction are among the most human activities that endanger our environment and ecological system. The enormous amount of resources that are consumed, the alarming amount of CO_2 emissions that are produced and the huge contamination at the end of buildings life are some but not all aspects. According to the USA Department of Energy more than 30% of the global greenhouse gas emissions (CO_2) are caused by buildings (UNEP SBCI , 2009). Three billion tons (40%) of raw materials are consumed by buildings annually (Lessen & Roodman, 1995). In addition to that, satisfying society's needs most of the time is accompanied with increasing dependent on non-renewable materials (Ashby, 2009). The building industry also generates more than 410 million tons of waste per year and increasing only in Europe as the European environmental agency indicates (Durmisevic, 2010).

Architects and engineers together with contractors and owners have taken their place in the universal effort to return balance to the environment. This effort could be noticed through the sustainable architectural movement and the emergence of sustainability assessment and rating systems in the building sector since BREEAM was launched in 1990 (BREEAM, 2010). No doubt that the new ideas and innovations which have been introduced to the sustainability of architectural design have made a difference in the reality of building industry. However this development in the design process was not accompanied by similar innovations in the construction of these buildings. Also, the little concern which was given to the life-cycle-design of buildings and specifically concrete building and the little attention to the end-of-life phase was not enough to move toward a holistic approach to sustainable construction.

Problem statement

Despite the effort which has been made to assess the life-cycle of buildings, its components and materials and because this life-cycle model for concrete buildings is still linear, the stress caused by the consumption of resources for the production of new materials and elements on the environment remained without change. The linear life-cycle model "cradle-to-grave" which distinguishes the concrete buildings prevents from reuse of their elements and materials. Reuse of concrete elements from buildings is supposed to help in decreasing the previously mentioned environmental impacts and make buildings more sustainable by reducing the construction waste and demands on raw materials.

At the same time a lot of concrete buildings around the world end its function while their elements are able to serve longer time. This can be conceived from the Euro Code – basis of structural design which gives indicative design working lives for the design of various types of structures as will be discussed later.

One reason that interrupts the reuse is the current methods of dealing with concrete in buildings for both cast-in-situ and precast systems. These methods produce monolithic interpenetrating entities that gather all functions in one monolithic unit. These units have only one end of life scenario the demolition.

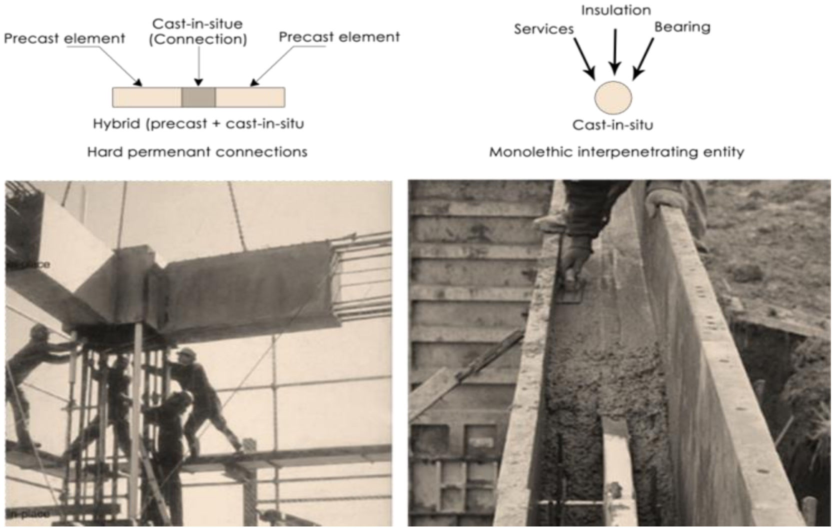


Figure 0-1: Cast-in-situ and hybrid construction types of concrete buildings and representation for their disassembly hindrances based on the definition of Durmisevic (New Zealand Concrete Society, 1999), (precise forms, Inc, 2016)

Imagining the amount of concrete that needs to be demolished and dumped at the end of buildings service life should alert and motivate for other intelligent solutions. Due to the fact that a considerable amount of concrete buildings and structures around the world end their service life and be demolished while their elements still be able to serve longer time, some voices around the world have been raised to consider the demolition as a design error. On the other hand, the concrete technologies are very open to continuous developments and improvements that make them more environmentally friendly, more efficient and smarter. Nowadays the development of various concrete technologies opens the door for new applications and practices. Therefore, it was crucial to modify the life-cycle-model of concrete buildings to a more cyclic one by altering the way buildings are designed and constructed. Also, by making it possible to reach components and materials for reuse and update. This could be achieved by adopting design for disassembly DfD.

The current status shows that further research regarding DfD for some groups of materials is needed. Concrete buildings are one of the three main types of structures (concrete, steel and timber) that need to be substantially investigated, analyzed and studied with regard to DfD.

Also actions are needed to move DfD from theory to practice. This study will help to bridge the gap in two ways. First, it will reposition concrete components and materials into cyclic loops. Second, it will move the concrete structure to a position of competence with steel and timber structures regarding flexibility, reusability and disassembly.

Design of buildings so that it will be easily later disassembled for reuse and recycling was made possible by gardener Joseph Paxton long time ago in 1851 when he comes out with his well-known historical structure Crystal Palace in London. This example considered at that occasion a new notion regarding physical building integration as Durmisevic believes (Durmisevic, 2010). In the 1960's, groups such as Archigram in Britain and the Metabolists in Japan were experimenting with building systems where disassembly possibilities can highlight the aesthetic character of the building (Crowther, 2005). Despite that this attempt has been followed by other attempts such as Shanghai Bank or Pompidou center where these buildings are called now reversible buildings or circular buildings, the majority of these attempts were restricted to steel structures. Concrete structures have been ignored in this context and only little attempts have been made. One unique example could be noticed is the CD20-system which has been developed in the Netherlands primarily for quick assembly.

Research question

This research project is supposed to give answers regarding the potentials and limitations of concrete buildings, their components, elements and materials with regard to their disassembly potential and transformation capacity.

Aims and objectives

The holistic approach to sustainable construction required involving all construction and building aspects in a system of development. Concrete structures have aspects that require more attention, such as reusability and flexibility of components and elements. Such consideration can move these buildings to a higher position in the world of sustainability. As a response not only to sustainability and environmental awareness but also to the continuously changing needs of people this study proposes that concrete - as a building material - could contribute to the adaptability and flexibility of the functionalities of the building. It also could contribute to the reusability of elements and components through DfD. This study aims at analysis of the potentials and limitations of concrete buildings and their elements with regard to DfD and consequently transformation capacity. It also suggests developments to some common precast concrete systems to make them more sustainable.

Contribution and added values

This research project will add value to the construction of sustainable concrete buildings through activation of cyclic loops in life-cycle design of buildings, its components, elements and materials. This would be possible through the development of precast concrete building systems to have higher disassembly potential and transformation capacity. It will also contribute to the current research and development in the field of sustainable construction and life-cycle-design through encouraging, promoting and pushing toward sustainable innovative solutions in architectural construction technologies that have less environmental impacts.

Scope and focus of the study

The study reviews the state of the art regarding demountable building systems, concrete systems and technologies, and DfD of buildings. The study analysis and evaluates the precast concrete systems regarding their disassembly potential and suggests concepts for the development of some common precast façade systems. The reason behind choosing façade systems is based on the fact that the enclosure system has a higher exchange rate than the load bearing system and a more architectural significance on the building level than that of the infill system. It also has more complicated aspects due to the various functionalities that it provides the building with, which makes it a rich material to be studied.

Methodology

The research methodology can be described through four main stages: material and data collection, analysis and interpretations, category selection, evaluation and development of concepts. As this study is trying to develop sustainable DfD systems for the construction of the concrete buildings the following research design has been considered.

Research design

The study started with a review of the theories and literature of DfD as well as classical demountable building systems and their demountability characteristics. Then analysis of the possibilities and limitations of precast concrete elements and material based on the DfD theories has been applied. The analysis has revealed results that have been interpreted for the design and development of new concepts and technologies which provide higher disassembly potential of systems (see figure 0-2).

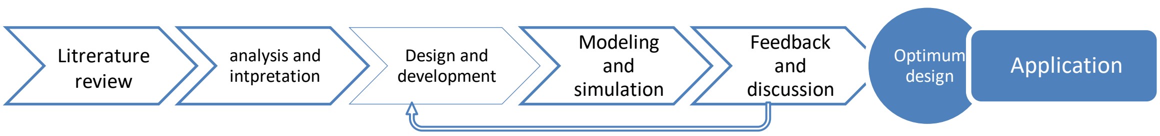


Figure 0-2: Research design

Data resources

- Review of the state of the art has been obtained from books, journals, institutes publications and official internet sites.
- Interviews with experts, architects, contractors and engineers from the industrialized sector have also been held (see appendix 1).
- Questionnaire to explore experts and specialist’s opinion regarding some arguable questions and specific issues (see appendix 2).

Thesis Overview

The following figure provides an outline of the dissertation including lead-in materials, core materials and lead-out materials. The lead-in materials include chapters that will review the state of the art. The core material includes chapters that will analyze and evaluate the current building systems and chapters that will propose developments of systems. The lead-out materials inlclude chapters of conclusions and recommendations. Chapter one reviews the state of the art regarding the construction of concrete buildings, chapter two reviews the state of the art regarding design for disassembly of buildings. Chapter three, four and five utilize the theory of chapter one and two for the analysis of precast systems of the three physical levels of concrete buildings including structural, infill and the enclosure levels.

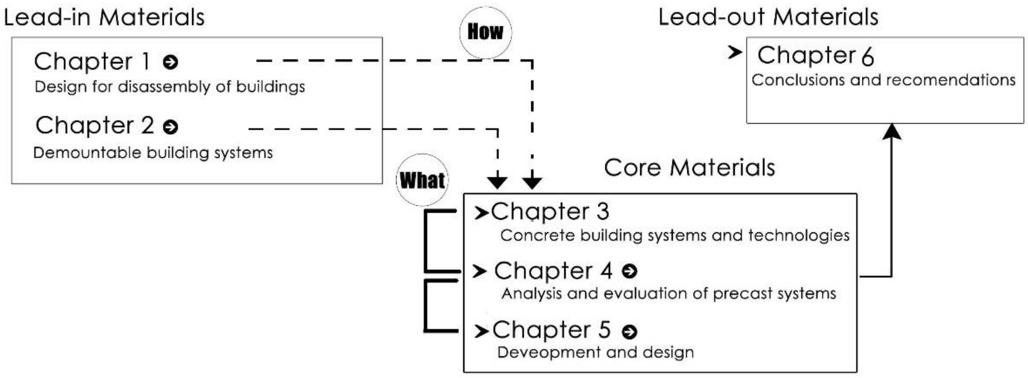


Figure 0-3: Thesis overview and relations between chapters and parts

State of the art

This section aims to explore and review state of the art regarding designing buildings for disassembly and the expected environmental benefits. Starting with the green or sustainability rating systems a review of the most popular ones such as LEED, BREEAM, DGNB and GREEN GLOBES shows the specific attention that these rating systems consider regarding disassembly of buildings. For example, DGNB, the German rating system, gives deconstruction and disassembly of buildings a relevance factor of 2 and a share of the total score of 4.1% and corresponding to a maximum score of 10 evaluation points. DGNB also considered the importance of ease of disassembly, recycling and disposal plan indicators for dismantling and recycling of the building structure (DGNB, 2014).

A study carried out by Philip Crowther discussed the existing model of building materials and components which are often referred to as “cradle to grave” model in which the building ends up as waste. Crowther suggested a new paradigm toward life-cycle, reuse and recycling of materials and components (see figure 0-4). Crowther sees that not only the physical breakdown of the materials and components that defines the end time of the building but also the cultural and social change to which the building can no longer respond. He explained the impact of the current model and gave an example that shows a loss of 25% of the building's total construction and operational energy use by the act of demolition, especially for buildings with short life span (Crowther, 1999).

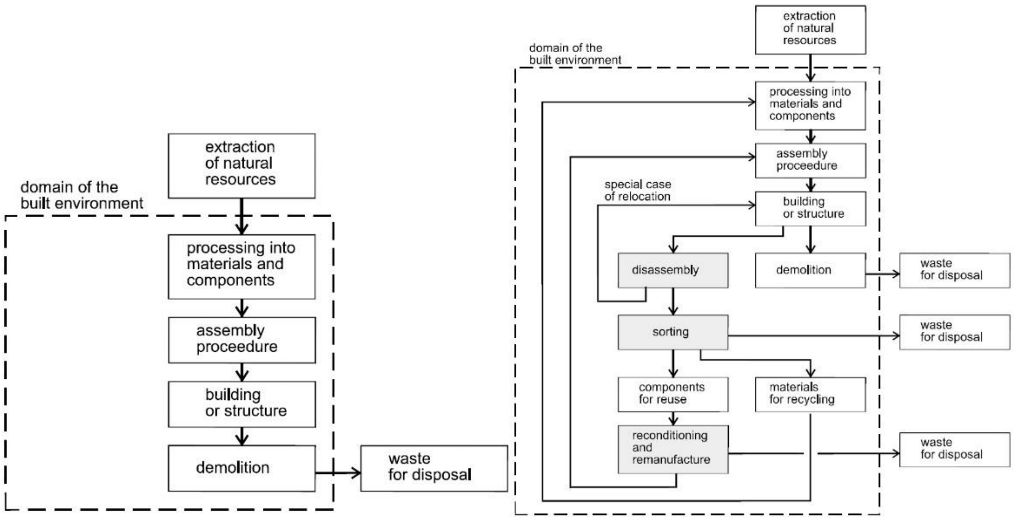


Figure 0-4: To the left, the dominant model of the life-cycle of materials and components. To the right, an alternative sustainable model for life-cycle of materials and component (Crowther 1999)

In a more recent study Crowther highlighted that two types of knowledge with regard to DfD existed. firstly, broad themes that deal with: why, what, where and when to DfD, secondly the direct question how to DfD (Crowther, 2005). Another study By Luiz Verfago and Jaume Avellaneda was carried out to introduce a new concept regarding materials and building elements that reach the end of their function and to evaluate the potential for recyclability. They provided a definition and introduced the concept of “index of recyclability”, “index of design recyclability” and “index of deconstruction recyclability. They performed calculations to verify recyclability of timber, steel and concrete structures and concluded that the index of deconstruction recyclability of a conventional concrete buildings was infra-use (Vefago & Avellaneda, 2013). A. Akbarnezhad et al. carried out a study to assess the economic and environmental impact of deconstruction strategies using building information modeling by developing a potential application to be used at the deconstruction stage of the buildings. Their study included a case of a 14-story building where all the structural beams, columns, slabs and wall panels can be designed for disassembly and reuse with consideration of DfD-connections. The results showed that additional initial cost, energy use and CO_2 emissions accompanied the fabrication of DfD-components compared to conventional; however, a significant reduction in the construction cost in the second cycle of service life was achieved(Akbarnezhad, Ong, & Chandra, 2014).

Furthermore, Elma Durmisevic considered the balance between the increasing dynamic of change and the key principle of sustainable engineering. She believed that extending the life-cycle of buildings and their materials could be through a new design approach. She discussed in depth how to manage the mismatch between the “use life cycle” and “technical life cycle” of building assemblies. Durmisevic also provided a design framework for high disassembly potential of building structures which result in a high transformation capacity TC. She believed that a high TC of a building relies on their high disassembly potential which is an indicator of building or system’s flexibility and environmental efficiency.

Durmisevic developed a knowledge model that considers various aspects of DfD. She found that this knowledge model formed a tool to compare individual aspects of transformation and to assess aspects and their impact on TC which resulted in a final TC-index that evaluates configurations. Durmisevic suggested further research regarding the analysis of the possibilities and limitations of different material groups with regard to DfD and consequently TC (Durmisevic, 2010).

It can be concluded from the previously reviewed studies that at the time Crowther discussed the benefits of DfD and introduced basic concepts of understanding time-related building layers and hierarchy of recycling. Moreover, Verfago and Avellaneda reviewed the recyclability of materials and their ability to be recycled and provided ideas about the degree of recyclability. Both of these studies were essential to the understanding of DfD and recyclability of materials. Durmisevic went beyond the previous approaches in considering DfD. She discussed in depth all of the aspects that affect and affected by DfD-process and provided a broader experience in dealing with the transformation of buildings as a system composed of interdependent subsystems. The author believes that this research project is going to be a continuity of Durmisevic work and it will make use of her findings, analysis and conclusions to move forward the DfD of concrete buildings not only theoretically but also practically.

DfD why was not using concrete elements - why it is possible now?

The following table shows the main points that clarify the reasons why DfD was not applied to concrete elements in the past and why it is possible now to be applied.

N.	In the past	Now
1.	Conventional methods are dominated by cast-in-situ construction.	Precast construction is finding more interest and is widely used.
2.	Cast-in-situ construction produces monolithic interpenetrating entities.	Precast elements can be easily separated due to that fact that they are produced as independent elements.
3.	Concrete elements are heavy, transport and installation have been a problem.	Heavy weights are not a problem any more due to automation and machines.
4.	Jointing of façade elements has been a problem.	Development of new jointing materials and techniques provided suitable solutions.
5.	Concrete technology was primary.	The developments in concrete technology provided new applications and solutions.
6.	Reuse of concrete elements was not a norm.	Reuse is highly required and encouraged nowadays.
7.	Dominant type of concrete buildings was cast-in-situ where cutting elements was costly and dangerous.	Precast elements are used for many building types and applications nowadays.

Chapter 1. Design (of buildings) for disassembly

Introduction

The notion toward designing building for disassembly is a new concept that has environmental root; the concept is already applied to automobile industry, technology and machines. The development in building and material technologies should facilitate for such new concepts to emerge in the field of architecture and building to rival other fields. Providing buildings with disassembly potential rings environmental and social benefits (Crowther, 1999). This chapter shows state of the art regarding DfD of buildings, help in showing why, what, where, when and how to DfD. It also reviews the challenges and opportunities that face DfD. Finally, it presents the evaluation criteria that will be followed by the analysis and assessment of the building levels of concrete buildings.

1.1 Understanding DfD

In order to provide a complete picture about designing buildings for disassembly the following sections will consider the five questions why, when, what, where and how to design buildings for disassembly and review the state of the art.

1.1.1 Why to Design for Disassembly

One of the main reasons behind DfD of buildings is avoiding the terrible high rates of waste generated by demolition. Many benefits also could be obtained such as extending the service life-cycle and encourage the reuse and recycle of materials and components (Crowther, 1999). According to Mark D. Webster et al. this approach reduces the adverse effect of resources consumption that leads to depletion of these resources (Webster & Costello, 2005). According to Fernanda Cruz Rios et al. some social, economic and other benefits could be gained through the process of DfD such as creating gob opportunities, due to the labor-intensive nature of disassembly process of buildings. According to her, economic benefits could be visible as soon as the DfD principles become more acceptable. Rios et al. believe that other benefits could be the historic preservation of building materials and components (Rios, Chong & Grau, 2015). Elma Durmisevic believes that buildings must respond to dynamic and changing demand of users. She believes that the buildings will be able to be reconfigured and reused when it starts to transform as a result of disassembly potential.

Also DfD will facilitate maintenance and reconfiguration of various parts of the building and move buildings from closed static systems to open transformable systems (Durmisevic & Yeang, 2009). DfD also presents a more economical and useful approach to overcome obsolescence and extend the economic life of building which has a significantly longer physical life (Crowther, 1999). (See figure 1-1) (Durmisevic, 2010, p. p.92)

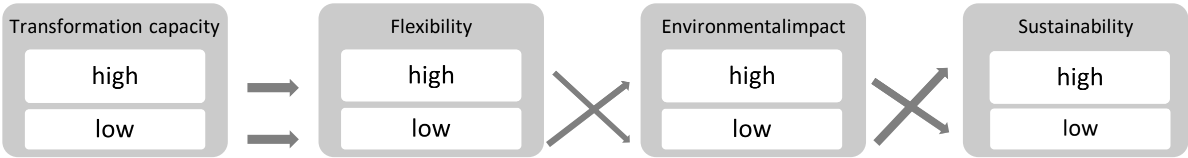


Figure 1-1: High transformation Capacity = High Sustainability (Durmisevic, 2010)

1.1.2 What and where to Design for Disassembly

DfD is a common practice in technology and automotive industry. Almost every part of the car can be dismantled for maintenance or replacement. Car manufacturers have started to design standard parts that are compatible with many types of vehicles (Gines & Beorkrem, 2009). Buildings also consist of elements and components and these components differ in their life spans. Durmisevic believes that all material levels that are accounted for by the technical composition of buildings should be affected by DfD (Durmisevic and Yeang 2009 p.135-136). Technical composition within a building systemizes materials according to a desired function and arrangement and integrates them into a specific physical level (Durmisevic, 2010, p. p.103). Catalli believes that analysis should be focussed on five levels within the building design process:

1. Systems: adaptable buildings those are changeable according to different conditions such as modular buildings that could be assembled and disassembled for reuse
2. Elements: foundations, walls, roofs and columns, modular and panelized elements are the target of this analysis
3. Component or assembly: non-structural combinations of several subcomponents
4. Subcomponent: break down a component into its smaller pieces
5. Materials: most basic materials that could be reused or recycled (Catalli, 2009).

The time-related building layers consider an important concept that helps to understand what to DfD. John Habraken in 1998 indicates two layers of buildings; structure or support and infill or space defining elements. The structure has a long service life and accommodates potential to the infill to be modified (Crowther, 2005) (Durmisevic, 2010, p. p.97). Duffy and Brand studied the building with relation to its layers. Figure 1-2, 1-3 show the definitions that Duffy and brand gave to the building (Durmisevic, 2010, pp. p.99-100). Mathew Gines and Chris Beorkrem argued that the architect is responsible for deciding what to be DfD and at what level; whether to design the entire building, the interior, the structure, the façade or any other entity. It can be through assessing the life span of building elements and parts and through discussion and analysis with the client (Gines & Beorkrem, 2009).

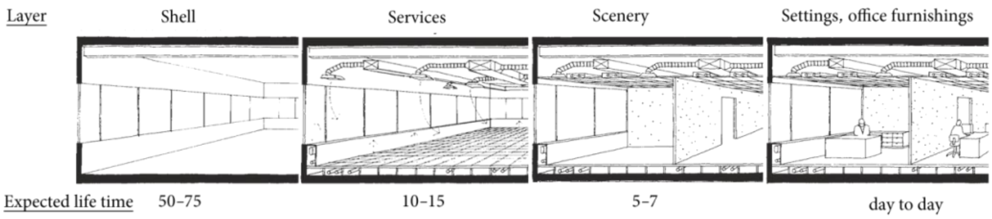


Figure 1-2: Buildings layers according to Duffy 1998 (Durmisevic, 2010)

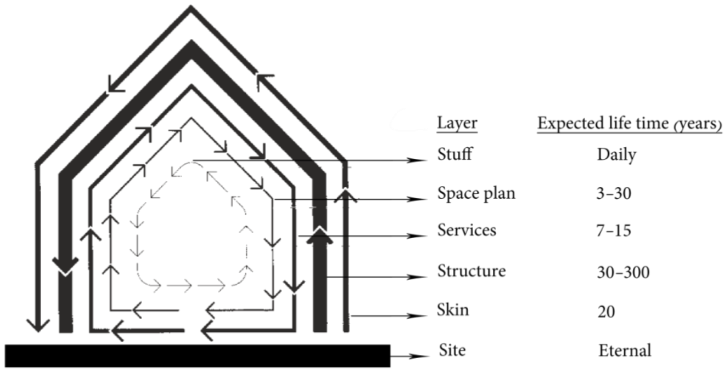


Figure 1-3: Building layers and their expected lifetime according to Brand 1995 (Durmisevic, 2010)

Again the importance of understanding building layers to DfD, as well as future building adaptability, could be seen in Peter Graham's explanation. He believes that disassembly has to occur at the junction where layers meet. The proper design of this junction for the sake of disassembly will provide the building with the ability to adapt to change in a sustainable manner (Crowther, 2005). Danya Sturgess studied the joint from an aesthetic, architectural and constructional point of view and their relation to assembly and disassembly characteristics. Moreover, the Dutch architects Ben Van Berkel and Caroline Bos discussed the perception of details and joints as factors that extend the appreciation of architecture and demonstrate disassembly. They also appreciated the effort and skill in detailing these joints. Sturgess believes that articulating joints based on the expected endurance of components and layers could be a possible strategy for assembly and material life-cycle (Sturgess 2012 p 43-53). Elma Durmisevic studied the aspects of the design of connections with relation to the physical decomposition of the building which will be discussed in "How to DfD" section.

1.1.3 When to Design for Disassembly

Referring to the model proposed by Charls Kibert (1994) of the University of Florida which embodies the three principal axes of sustainable construction; life-cycle stages, strategies for sustainability and environmental resources. The various numbers of issues that relate to sustainable construction and their interrelations could be illustrated. This illustration can be useful to support the decision-making process during the construction of a project (see figure 1-4).

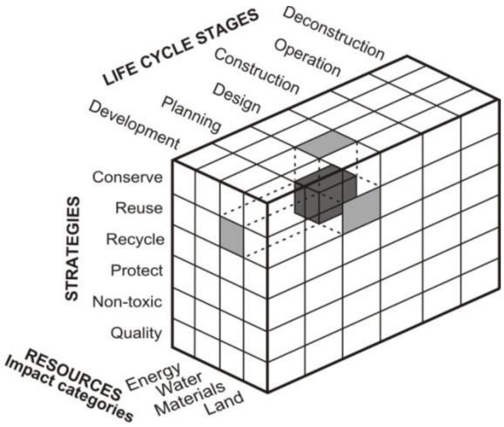


Figure 1-4: The modified model for sustainable construction indicates areas of concern to DfD (Crowther, 2005)

It can be noticed that the strategy of future reuse of materials could be considered at the design stage of the building life-cycle. Crowther believes that this model helps in solving problems and conflicts that may appear between alternative principles of DfD, such as considering recycling of materials to reduce waste which may need much energy than creating new materials. Or conflicts such as the use of long-life durable material which may be toxic (Crowther, 2005).

Since DfD is a tool for future reuse of materials and components and not a target or fashion standardized forms and generic materials are favors for DfD. At the contrary, custom forms are not suitable for reuse since the possibilities to suit new projects are limited (Sturgess 2012 p.19). It can be concluded that DfD is suitable to be applied when standardization and repetition exists. Fredrik Blom recognized the potential for manufacturing prefabricated elements for reuse on an industrial scale. He thought that a wall could be produced as a series of parts that could be assembled and disassembled according to demands (Bergdoll & Christensen, 2008). Another situation in which DfD could be applied is impermanence; some types of structures and buildings designed to serve a limited period, others exposed to change of function and use. To make use of their materials and components after the life of the building ends they must be designed for disassembly. Durmisevic argued that DfD is needed to avoid demolition when the technical life-cycle of the building or its systems is longer than the use life-cycle of the building or its systems (Durmisevic, 2010, pp. p 70-71). Clear evidence that emphasizes Durmisevic argument is the design working lives of buildings. According to the concrete society in UK the design working lives based on BS EN 1990, Euro code – Basis of structural design, (Euro Code 0) the working lives for the following various types of structures are as in Table 1-1.

Table 1-1: Design working life of various building categories according to Euro code.

Category	Design working life (years)	UK National Annex To BS EN 1990:2002 modifications
1. Temporary structures, not including structures or parts of structures that can be dismantled with a view to being re-used	10	-
2. Replaceable structural parts, e.g. gantry girders, bearings	10-25	10-30
3. Agricultural and similar buildings	15-30	15-25
4. Building structures and other common structures	50	-
5. Monumental building structures, bridges and other civil engineering structures	100	120

For all of the previously mentioned categories the technical service life of concrete is much longer, which provides the ability to reuse concrete elements more than one time in most categories of buildings (The concrete society, 2016).

1.1.4 How to Design for Disassembly

The aim of DfD is to facilitate the removal of layers for replacement, reuse or maintenance without exposing other layers to damage. "The first step toward design for change is to decouple independent levels that have different degrees of durability" (Durmisevic, 2010, p. p.79) . So the process of designing for disassembly required a complete understanding of the previously discussed topics regarding why, where, what and when to DfD. In addition to that a better understanding through analysis and study of buildings composition from a technical, physical, functional and material point of view as well as the study of configurations within these levels is of high importance.

1.1.4.1 Technical composition and physical levels of the building

The technical composition can be recognized through systematization of materials to provide a specific function with an arrangement and integration of materials into a specific physical level (see figure 1-5).

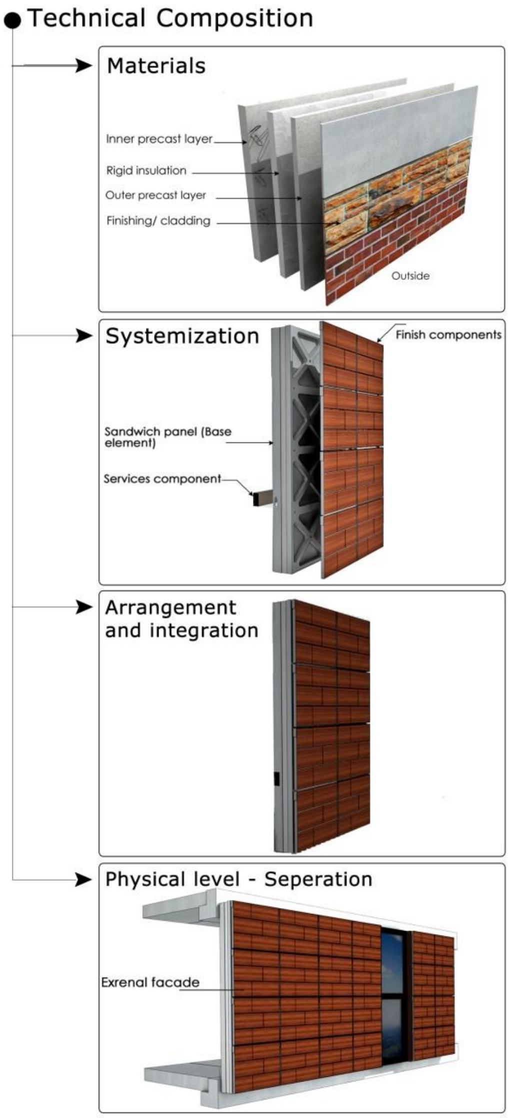


Figure 1-5: An example shows the technical composition of the sandwich panel system

Durmisevic believes that understanding the technical composition of a building - which is critical to the life-cycle of the building and its materials - requires a focus on both durabilities and interfaces as well as arrangements and relations of materials. For example, while some facades components could have 80-100 years technical life-cycle, their use life-cycle could be 20 years. This mismatch requires these components to be changed more than one time. In such cases facades should be independent at the building level. Also the durability of materials should affect the arrangement of materials levels. (see figure 1-6) (Durmisevic, 2010, p. p.103)

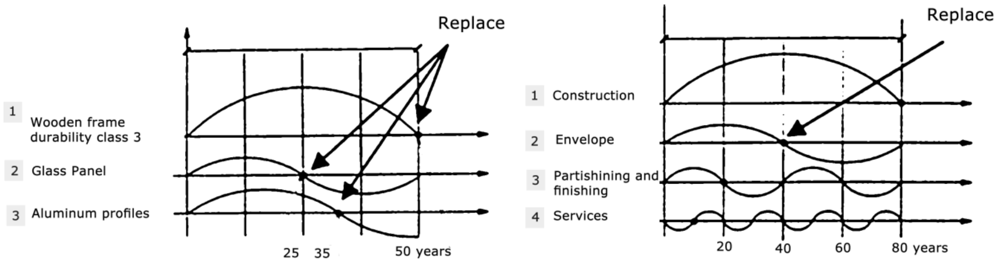


Figure 1-6: Different use and technical life cycles within a façade system (Durmisevic, 2010)

A relevant study by Suárez Fernández-Coronado and others presented and analyzed six case studies in which flexible architectural skins were used. These case studies show how by means of technology, buildings have gained the best comfort conditions and flexibility. They also gained the best value of money for the client through facilitating the replacement of façades and their components (see figure 1-7) (Suárez Fernández-Coronado, Inés & González Bravo, 2010).

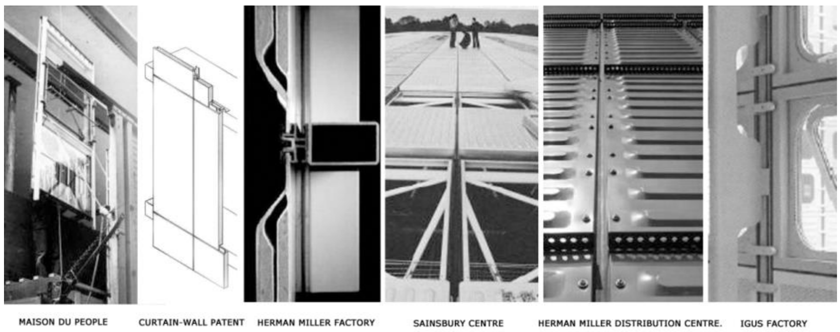


Figure 1-7: Flexible facades (Suárez Fernández-Coronado, Inés & González Bravo, 2010)

In her study of physical levels Durmisevic presented an example that shows the importance of emancipation of physical levels. Figure 1-8 shows how splitting the one fixed entity of typical concrete projects to a number of independent physical levels extends its life-cycle and facilitate change.

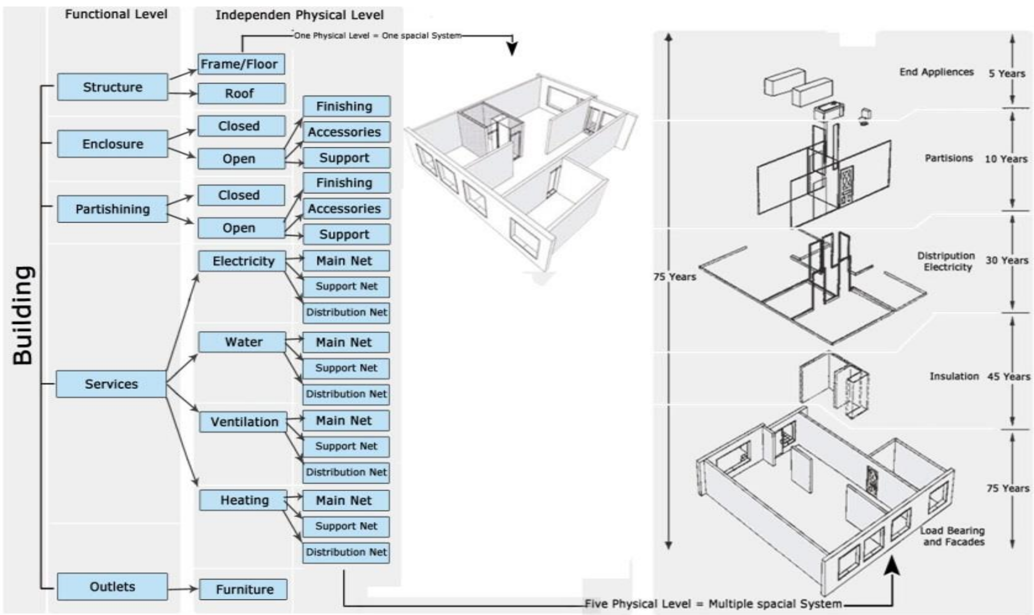
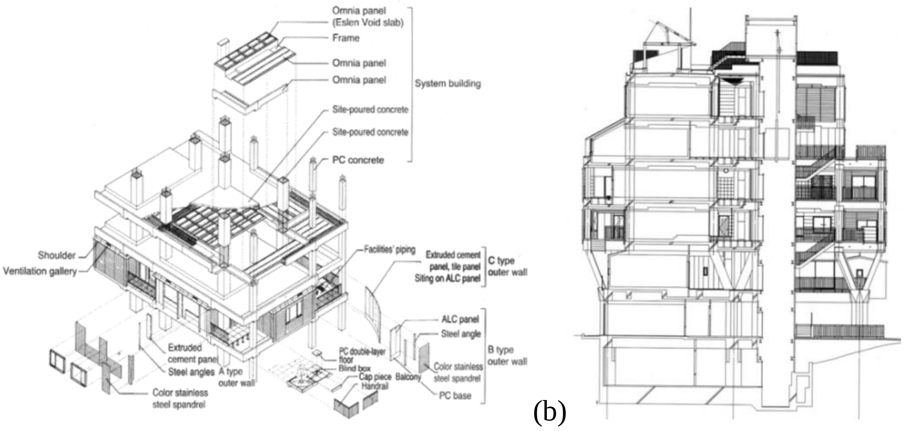


Figure 1-8: One fixed physical level system versus five physical levels (separation of levels facilitates change) (Durmisevic 2010)

An excellent related example that worth mentioning is NEXT 21 Complex House project in Osaka (Japan). The main concept of this project was to provide an adaptable building that accepts change and reconfiguration. The building was designed as an integrated system that consists and assembled of subsystems which are independent for flexibility (Kim, Brouwer, & Kearney, 1993).



(a) (b)

Figure 1-9: The emancipation of building components and systems in NEXT 21 Project. (b) a section in the project, (Ismail & Rahim, 2011), (PIVA, 2012)

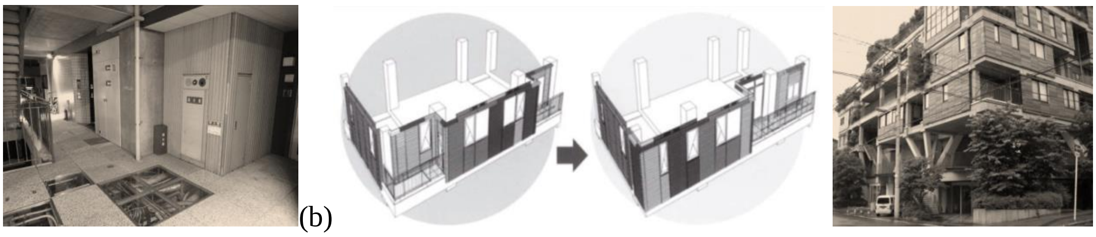
(a)  (b)

Figure 1-10: (a) mechanical systems could be easily accessed, (b) facades of the NEXT 21 project could be repositioned and changed to provide multiple alternatives (Wen & Ting, 2012), (Durmisevic, 2010)

- **The life-cycle coordination matrix**

To identify the physical levels and there materials in which mismatch between technical and use life-cycle exists, Durmisevic developed a life-cycle coordination matrix. She argued that, all elements within this matrix that show disproportion between the life-cycle types ought to be marked as disassembly sensitive and valuable parts of the structure regarding their environmental and economic benefits. Appendix 3 shows three coordination matrixes of different types of buildings, range from a typical project to a flexible dynamic one. The first matrix represents the typical project which resulted in fixed technical system of one physical level. The second matrix represents a project in which a range of adaptability is required. And the third matrix accounts for a project where a dynamic total change of spatial system is required. This process includes separation of building functions according to a use strategy which ranges from fixed to fewer dependent conditions (Durmisevic, 2010, pp. p. 108-113). One good example of separation according to the use strategy could be noticed in IGUS factory in Cologne, Germany. In this factory the nature of the ever-changing work required continuous reconfiguration. Some of the most important features of this plant are the open lattice tension steel structure that frees the interior from columns and the external facades panels that can be repositioned and replaced easily (see figure 1-11) (Fuster et al., 2011).

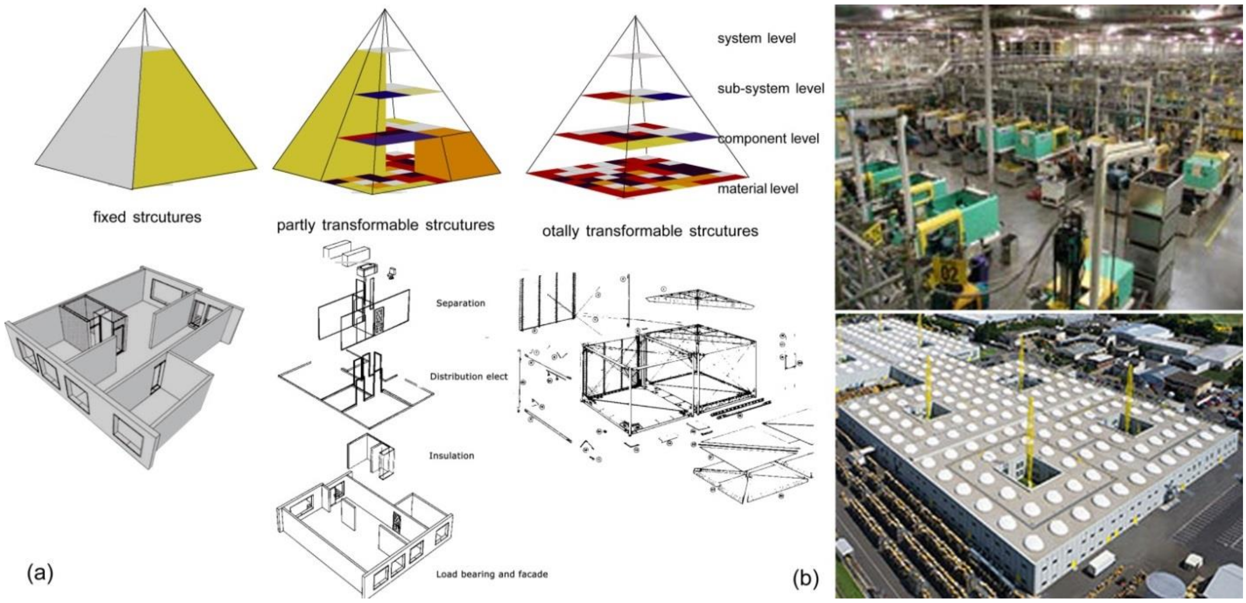


Figure 1-11: (a) types of structures regarding their transformation ability (Durmisevic 2010),(b) Igus Factory (Igus.de)

Durmisevic believes that another important criterion of technical composition of transformable structures is exchangeability. She argues that not only materials but also arrangements of these materials create independent physical levels of technical composition of a building (see figure 1-11).

1.1.4.2 Configuration design as a key to disassembly potential

According to Yu, relationships and arrangements of elements are the key factors that determine the type of configuration in a design process. These hierarchal arrangements affect the structure of the building and its future disassembly. Three main domains are involved in this process: functional, physical and technical. The functional domain represents the function on the building levels such as carry loads, separate spaces and other services. The technical domain deals with the composition of the building and building products that carry the previously mentioned functions, in other words use of technology for the composition of the structure. The physical domain describes the physical relations of parts and their relations within an assembly. According to Durmisevic, these domains cannot be separated in the decision-making process.

- **Typology of configuration**

Durmisevic believes that material levels, technical composition and physical integration are main elements that define the typology of every configuration. These typologies identify the transformation capacity through independence and exchangeability and decide the disassembly potential of a structure (Durmisevic, 2010, p. p.139). Furthermore, independence and exchangeability have lead Durmisevic to understand the building in a system approach (see figure 1-12).

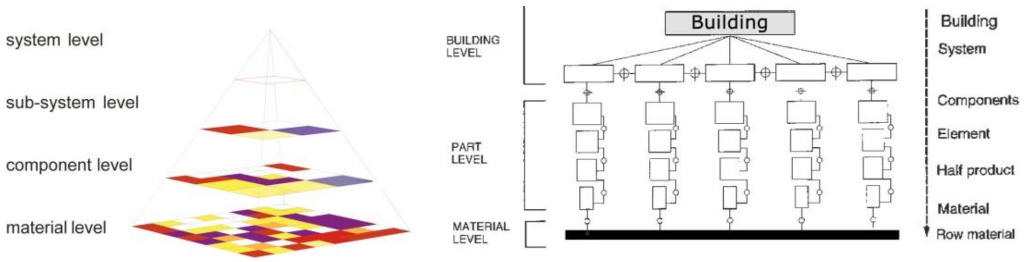


Figure 1-12: To the left: system approach to the building (hierarchy of material levels), to the right: systematic integration of material levels in the building (Durmisevic 2010)

- *Material levels*

The greatest transformation capacity could be obtained through the specification of the material levels when independence between assembly and sub-assembly as well as function and sub-function exists. That is why focuses few functions within one fixed material level caused static configurations.

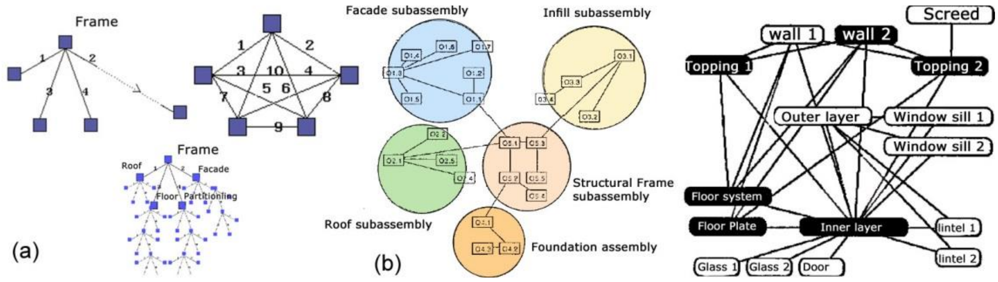


Figure 1-13: (a) various types of hierarches for open and closed systems, (b) relational diagram indicate the relation between components of building level and system level for an open and static structure according to R. Horden And Kapteijns et al. 1998

- *Technical composition*

Durmisevic also recognized that specification of the hierarchy of parts also affected by independence and exchangeability. Figure 1-13 shows two types of the hierarchy of building element: a closed conventional building and an open one and a relational diagram which clarifies the dependence between sub-assemblies and number of relations. Durmisevic believes that evaluating the real transformation capacity required analysis of more types of relations such as assembly relations and life-cycle relations as well as types of relations regarding the connection (Durmisevic, 2010, pp. p. 139-144).

Figure 1-14: KUBIK experimental project (Chica, José A, et al.)

A relevant example that shows dependencies of systems and subsystems is KUBIK. This experimental project tends to develop new concepts, products and services to improve the energy efficiency of buildings through the use of adaptable infrastructure facades, floors and infill using dry connections. Standarized and prefapricated elements and components were used in this project (see Figure 1-14).

-Physical integration

In addition to the previously mentioned factors that affect the independence and exchangeability, specification of interfaces and physical integration also has an effect. Three aspects can decide the physical integration between the elements: connections types, the geometry of product edge and the assembly sequence. Table 1-2 shows the difference between open and closed systems regarding these aspects**.**

Table 1-2: Closed and open systems with regard to specification interfaces - physical integration according to Durmisevic

system	Type of connection	Geometry of product edge	Assembly sequence
Closed	Chemecal	Result in stuck assemblies	Dependent assembly sequencies
Open	Accessible fixing	Simple	Independent

1.1.4.3 Decomposition of buildings

Independence of parts of a building structure and design of interfaces of these parts for exchangeability are key factors that decide how decomposable the building is. Durmisevic argued that some aspects regarding independence and exchangeability affect the decision-making during the design of decomposable structures. These aspects can be categorized into eight categories:

1. Functional decomposition,
2. Systematization and clustering,
3. Hierarchical relations between elements,
4. Base element specification,
5. Assembly sequences,
6. Interface geometry,
7. Type of the connections, and
8. Lifecycle coordination in assembly/disassembly

- **Functional decomposition**

Functional decomposition of buildings involves decisions regarding functions in a building product or component and this usually occurs during specification of material levels. A building product may carry one or two functions. Separation of these functions depends on relations between elements which are affected by geometry and interfaces as well as the creation of sub-assemblies. Two aspects of functional decomposition can be distinguished: functional independence and systematization of materials. Figure 1-15 shows the levels of functional independence in five different wall systems. It can be noticed how the separation of functions affects the demountability of wall elements.

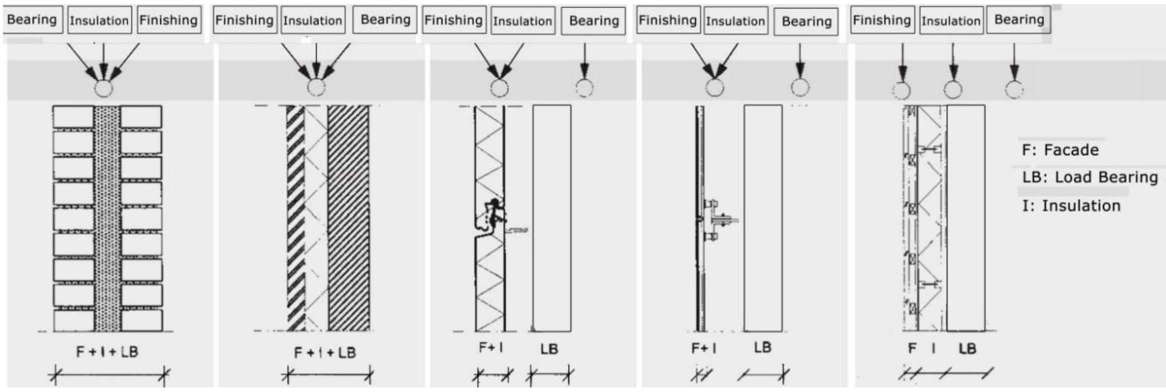


Figure 1-15: Levels of functional independence in wall systems (Durmisevic, 2010)

Systematization and clustering

Systematization of materials deals with clusters in sub-assemblies with relation to life-cycle performance requirements and the level of integration in the material levels. The importance of decisions made regarding systematization come from the fact that it could decrease the work on the site and facilitate assembly and disassembly (Durmisevic, 2010, pp. p.155-167).

- **Technical decomposition**

Technical decomposition deals with the order within a configuration which is defined by: relational patterns, type and position of relation and the base element specification. Relational patterns decide whether the building is decomposable or not. Durmisevic recognized six types of relational patterns: closed, layered, stuck, table, open and shared assembly. The simpler the relational pattern is the more decomposable the system become (see figure 1-15, 1-16).

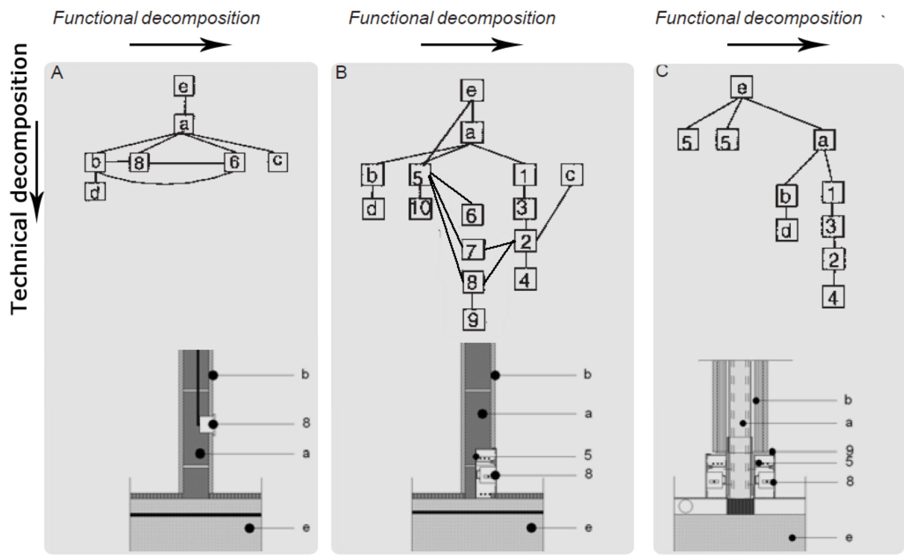


Figure 1-16: The different position of relations within a wall resulted in different configurations (Durmisevic, 2010)

The position of relation can be distinguished through vertical and horizontal oriented relations. Vertical relations deal with one function group while horizontal relations deal with relations between different functions groups. The more vertical relation diagrams the building has, the more dynamic it becomes. Figure 1-16 shows three types of configurations: static, partially dynamic and totally dynamic wall systems. The third aspect that defines technical decomposition is base element specification which makes independence of elements within cluster and elements within other clusters (Durmisevic, 2010).

- **Physical decomposition**

The physical decomposition deals mainly with the design of connections that facilitate disassembly and transformable potential of buildings. Four design aspects are involved: geometry of product edges, assembly sequences, type of connections and life-cycle coordination. Durmisevic sees that product boundaries and its geometry affect the disassembly sequences, where the interface design and specification of the connection type decide the degree of disassembly that will be occurred. Two types could be defined: open and interpenetrating geometry, in most cases interpenetrating geometry limits the disassembly to one direction (see figure 1-17).

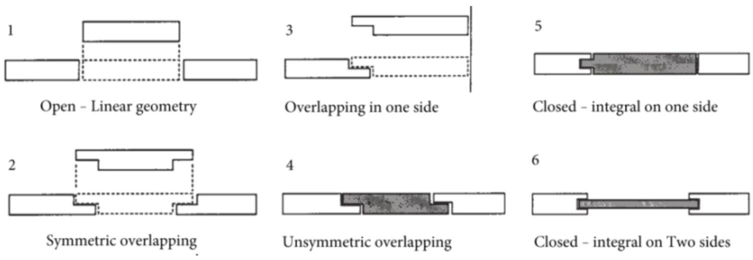


Figure 1-17: Different types of geometry of product edge that influence the level of physical decomposition and transformation level of configuration (Durmisevic 2010)

The second design aspect that affects the physical decomposition is the assembly sequences, building elements are locked together by some kind of assembly sequences. According to Durmisevic assembly sequences could be either parallel or sequential. Parallel assembly makes building and disassembly faster, while sequential create dependencies and complicates substitution. Other forms of assemblies could be established by mixing of these two types (see appendix 4).

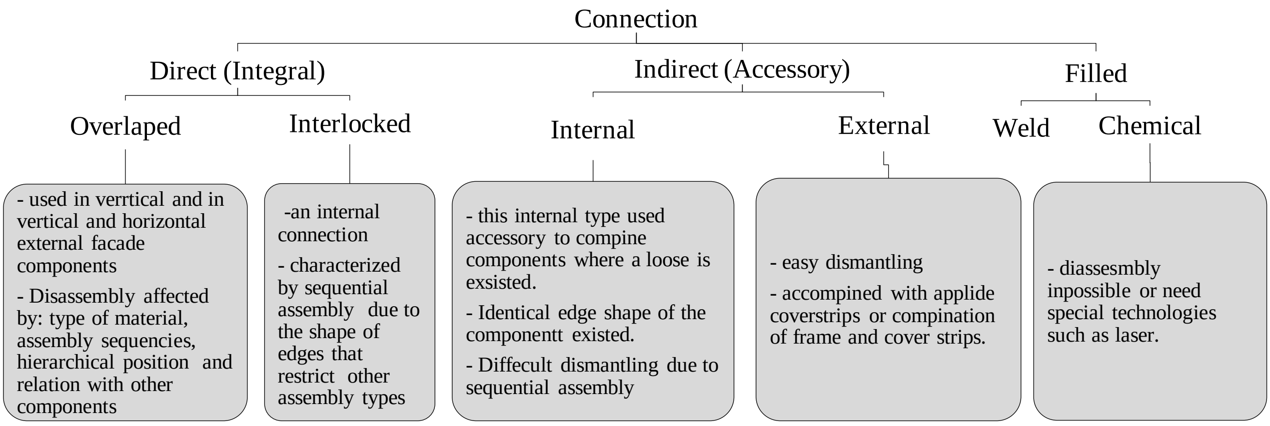


Figure 1-18: Connection types and their disassembly characteristics according to (Durmisevic, 2010)

The last aspect of DfD as Durmisevic believes is the design of building's connections. She argued that three main types exist: direct (integral), indirect (accessory) and filled. Figure 1-18 shows these types and their specifications (Durmisevic, 2010, pp. p. 173-177). The material in connections plays a major role in determining what kind of connection should be used and if it needs accessory of some type and where to position this accessory. The following table shows seven principles of connections range in their flexibility degree from fixed to flexible. The table also shows their graphic representation and their dependence in assembly (see appendix 5). To facilitate the disassembly of building materials and components life-cycle coordination should affect the assembly sequence.

This can be achieved by starting to assemble with long life cycle materials and ending with shorter ones to facilitate disassembly of such shorter life-cycle materials and prevent dependencies. Also assembly of materials should not only be affected by different life-cycles but also by functions that have different life cycles. Figure 1-19 shows how life-cycle coordination facilitates disassembly (Durmisevic, 2010, pp. p. 179-183).

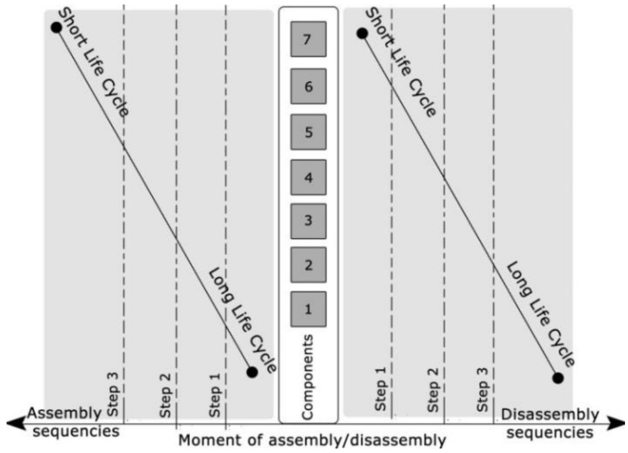


Figure 1-19: Assembly and disassembly sequences of components according to their lifecycle coordination (Durmisevic, 2010)

1.2 Challenges and opportunities

It could be noticed that three main areas regarding DfD of buildings are likely to face challenges. These areas include reuse, recycling of materials and disassembly of buildings.

1.2.1 Challenges regarding reuse

According to the U.S. Environmental Agency et al. buyers could be affected by the uncertainty of quality of material to be reused due to the different suppliers. This may impact the supply chain of these materials and elements. Such problems could be solved through the development of large material yards and the governmental and public involvement as well as building codes and regulations which tend to deal with such materials. Another issue according to S. Nakajima et al. is the lack of sufficient demand on such materials but this will be overcome as well as DfD becomes a common practice. M.D. Webster et al. see that inappropriate disassembly method could make components unusable. This usually caused by the lack of training, although this could be treated by detailed disassembly plan and alteration of jointing methods. Consumer taste also considered a challenge where such materials have suffered from a negative perception as the U.S. Environmental Agency believes. This could be solved by true successful projects and cases that could be done in reality as well as improvement of the materials to be reused, and the availability of assessment methods (Rios et al., 2015).

1.2.2 Challenges regarding recycling

W. K. Chong et al. consider transportation of salvaged materials for reuse and recycling is not worthy especially when it has to be moved far from its site. In such cases P. j. Dolan et al. see that development of the DfD practice will provide opportunities by increasing the recycling facilities. In addition to that more effective recycling technologies are needed for concrete since the most common use of recycled concrete is as base course for roads. A recent study by Shima, et al. resulted on development of an advanced concrete recycling technology which will be introduced in 2020. This technology employs the heating and rubbing method that produces aggregates that can be recycled as raw material for ready mix concrete. While fine powder (HRM) from cement paste can be recycled as raw material for cement, cement admixture or soil stabilizer (Shima, Tateyashiki, Matsuhashi, & Yoshida, 2005).

1.2.3 Challenges regarding DfD

C. J. Kibert et al. believe that another challenge regarding disassembly of buildings is the design process itself which neglect the end of life phase of the building and reuse of its materials and components. And that appear to be the first hindrance for proper disassembly of the buildings. Cost also considered an issue, where the general perception is the disassembly costs are higher than those of demolition. The higher costs are attributed to materials storage issues, labor and worker insurance costs, transportation of materials, training, market and demand and other challenges. A. R. Chini believes that some factors could reduce these costs such as the resale value, the partnerships and the governmental incentives. Lack of involvement and responsibility of important parties such as manufacturers is also considered challenging. Such issues need to be addressed by designers who are responsible for encouraging manufacturers to address the life of cycle information of their products. Another challenge to designing concrete buildings for disassembly is the suitability of dry connections for seismic areas. Generally, frames and structures need to be ductile for disputation of energy caused by earthquakes which help in resisting drafts and movement. Nevertheless, the emergence of damage resistant technologies has assisted in overcoming such challenge. This technology has been introduced to precast concrete since the late nineties in the USA good example of that is the precast seismic structural system PRESSS which was developed in the University of California, San Diego. This system showed sucsess during the 4th of September 2010 and 22^{ed} of February 2011 earthquakes that hit New Zealand when it has been used in Endoscopy Building of Southern Cross Hospital (Cement & Concrete Assoc. of New Zealand (CCANZ), 2012). In addition to that the department of structural engineering at the University of California has published a design guide on seismic drift compatibility of architectural precast concrete panels and connections ((ASCE), 2016).

Another issue that must be considered is the durability of concrete. Despite the durability of concrete as a building material, the use of steel reinforcement exposes the reinforced concrete elements to deterioration because of corrosion. When steel corrode the produced rust takes up a greater volume than the steel which causes tensile stresses in the concrete resulted in cracking (see figure 1-20) (PCA A. , 2016).

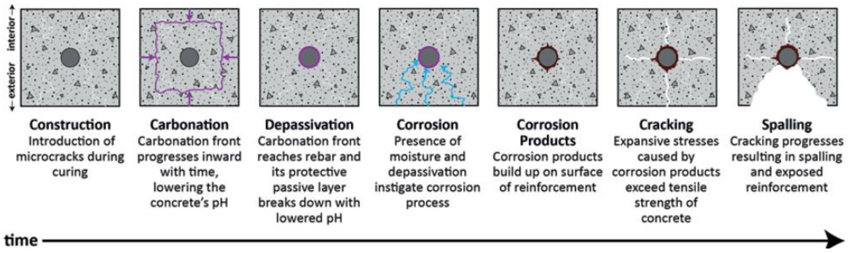


Figure 1-20: Deterioration of reinforced concrete through time due to carbonation (Meloy, 2016)

Many studies have been carried out to find solutions for the deterioration of concrete due to corrosion. Some suggest alternative rebar materials such as continuous basalt fiber CBF. This material could be made from the dense and abrasion-resistant igneous rock. CBF is 2.5 the strength to weight ration of alloyed steel and 1.5 that of glass fiber. Another alternative is engineered bamboo which is being explored as an alternative to steel. Some recent studies showed that woven-strand bamboo which is a composite developed material can resist moisture absorption, swelling and decay from bacteria (Brownell, 2015). Other studies explored the effect of waterproofing coatings on steel reinforcement corrosion. Also the use of a barrier system on the reinforcing steel such as epoxy coating, organic coating or metallic coating is of great importance (Smith, J.L.; Virmani, Y.P., 2000).

Other stakeholder-related challenges could be overcome through national planning and incentives (Rios et al., 2015). Finally, methods for measuring benefits of disassembly and reusability are still absent. Successful cases need to be documented and their data need to be published as a step to make benefits visible (Rios et al., 2015).

1.2.4 Opportunities

Fernanda Rios believes that despite the challenging aspects of DfD opportunities are existed and promising. These opportunities can be tangible through improvements of cost-effectiveness and feasibility as well as policies and partnership. DfD could increase the cost effectiveness of disassembly processes through reduction of time and labor need as Guy and Ciarimboli see. Others see that resales value of salvaged materials and the disposal savings highly affect the cost-effectiveness of the disassembly process. According to Rios EPA the disassembly provides 5% cost-effectiveness compared to demolition.

Policies and partnership could enhance the opportunities to DfD. Proper legislations not only can affect the economic feasibility of the used building materials market but also drive the artificial economy as S. Nakajima believes. According to I. Srour et al. a successful example could be learned from California which implemented such policy in the form of a governmental regulation that all projects have to recycle not less than 70% of their disposed materials. Another similar regulation according to the U.S. Environmental Agency prohibits landfilling of some material that could be recycled and reused could be found in Massachusetts.

The partnership between governments, the private sector, non-profits historical societies and other organizations can also make a difference in the success of disassembly approach and cost-effectiveness of the process (Rios et al., 2015).

1.3 Evaluation of disassembly potential

Assessing the disassembly potential of buildings is an important step that provides designers and planners with a holistic view regarding their disassembly aspects. Assesment is also critical to the development of the DfD process, not only it indicates the potential of a building for disassembly but also it defines the aspects of weakness that need to be further developed.

1.3.1 Evaluation models and their criteria

A few effort has been spent on this subject in research where the major effort was in the netherlands by a report to assess the capacity to change CTC index of buildings and their parts by OBOM research group in 1992. The report suggested that three aspects should be taken into consideration: separation of levels (site, support and infill), evaluation of load bearing structure in relation to building services and dependence between building elements. Another assessment model developed by Rob Gerards to measure the flexibility of installation services including aspects of spatial and technical flexibility. This model deals mainly with position, accessibility to services and capacity of the system. Later, Elma and Sanja Durmisevic developed a model to assess the spatial transformation with relation to the technical aspects. Their model involved the load bearing construction, the position of main installation net, the position of distribution installation net and their replaceability in addition to the replaceability of the partition walls (Durmisevic, 2010, p. p. 200). Later in 2010 Durmisevic developed a knowledge model to assess the transformation capacity of buildings that indicate their disassembly potential. Durmisevic believes that such model will help in better judgment of the sustainability of design solutions. As disassembly facilitate reconfiguration, reuse and upcycling of building elements, parts and components. Such processes are going to save materials, embodied energy, landfill costs, costs and energy for extracting transporting and processing of new materials and elements, as well as it will provide a broad range of special adaptability to buildings. After comparing various assessment models the author found that Durmisevic model was the most intensive one that takes into consideration most of the aspects that affects and being affected by DfD.

1.3.2 Durmisevic assessment model of disassembly potential

Information that deals with performance indicators of transformable structures acquired from buildings was used to develop this model. The independence and exchangeability of building elements considered being the defining design criteria for this model. Durmisevic believes that "*A building or system can be transformed if its parts can be defined as independent parts of a building structure and if the interfaces between parts are demountable*" (Durmisevic, 2010, p. p.201)

Table 1-3: A conceptual framework of the decision support evaluation model by Durmisevic (Durmisevic, 2010, p. p. 201)

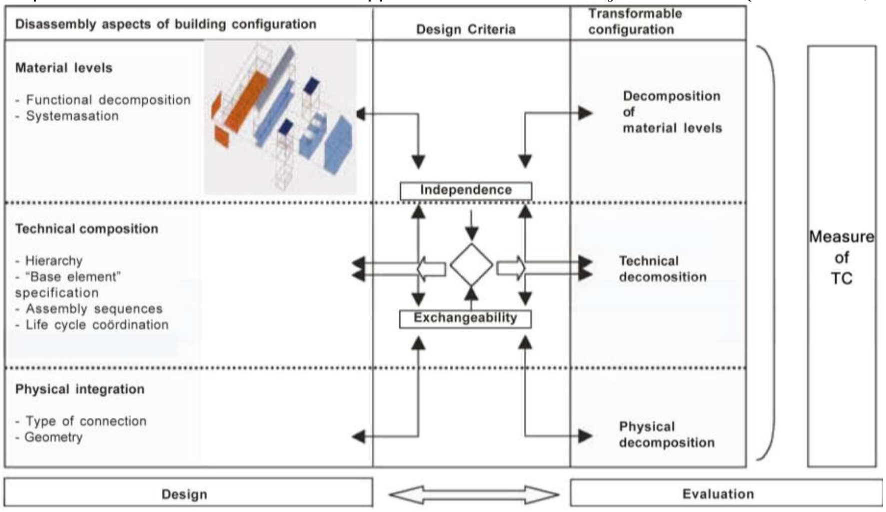


Table 1-3 shows how the independence of building parts is determined by decomposition of material levels and technical decomposition while exchangeability is determined by physical decomposition. The table also demonstrates the indicator of independence regarding material levels and technical composition and the indicator of exchangeability regarding physical integration. Furthermore, the table shows that: what determine to choose a material or not is the existence of feasible technical decomposition and what determine if this physical decomposition is valid or not is the presence of a feasible interface.

Table 1-4: DfD aspects and sup-aspects

	DfD aspect	***Abbreviation***	***Determining factor (D.F.)***
1	FD (Functional decomposition)	fs	Functional separation
		fdp	Functional dependence
2	SY (Systematization)	st	Structure and material levels
		c	Clustering
3	BE (Base element)	b	Base element specification
4	LCC (Life-cycle coordination)	ucl	Use life-cycle coordination
		tcl	Technical life-cycle coordination
		s	Coordination of life-cycle and size
5	RP (Relational pattern)	r	Type of relational pattern
6	A (Assembly process)	ad	Assembly direction
		as	Assembly sequence
7	G (Geometry)	gp	Geometry of product edge
		spe	Standardization of product edge
8	C (Connection)	tc	Type of connection
		af	Accessibility to fixing
		tc	Tolerance
		mj	Morphology of joint

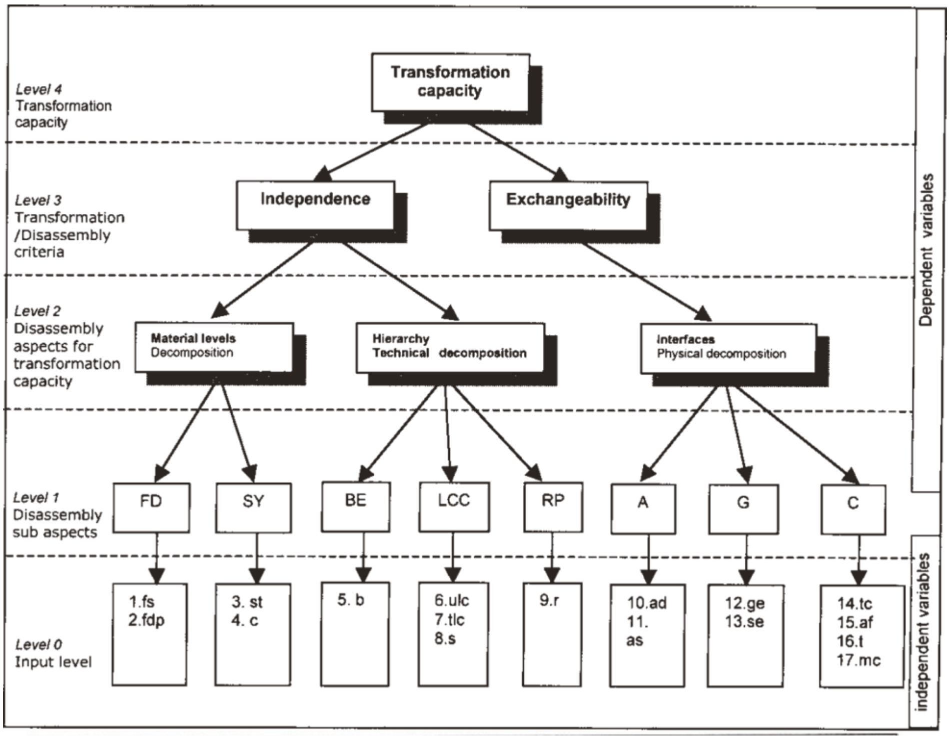


Figure 1-21: Hierarchal structure of Durmisevic disassembly potential knowledge model (Durmisevic, 2010, p. p.203)

Based on experts assessment of the different criteria which affect the disassembly potential of buildings, the input data for the model is provided. The model includes 17 independent variables and 14 dependent variables as in Figure 1-21and Table 1-4.

Level 0 which represent all sub-aspects have been given weighting factors that present the impact of each sub-aspect on the main aspect of DfD (see appendix 6).

The hypothesis that Durmisevic proposed was greater disassembly potential leads to increased flexibility and environmental efficiency which means greater sustainability. The proposed criteria were based on the concept of demolition and reuse. A value between 0.1 and 0.3 has been given to each aspect that leads to the demolition of components. A value between 0.3 to 0.6 have been granted to aspects that lead to partial demolition, and a value between 0.6 and 0.9 have been granted to aspects that lead to disassembly with possible reuse, reconfiguration and recycling (see appendix 7). According to that she divided all building types to three categories regarding their disassembly potential (see Table 1-5).

Table 1-5: Types of buildings regarding their disassembly potential

Type	Description
Type one	high disassembly potential structures where independence and exchangeability aspects have values more than 70% of the highest possible value (TC<0.67)
Type two	medium disassembly potential structures where independence and exchangeability aspects have values between 33 and 70% of their highest possible value (0.33<TC<0.67)
Type three	low disassembly potential structures where independence and exchangeability aspects have values less than 33% of their highest value (TC<0.33)

1.4 Conclusion

This chapter has discussed the design of buildings for disassembly, it has provided the state of the art, discussed the previous attempts, gave a clear understanding and indicated the challenges and opportunities. The following points could be concluded:

- Concrete is still preferable due to its strength, durability, ability to be formed, free from off-gazes, availability, relatively moderate cost and accustomed to it.
- Concrete buildings have been neglected with regard to DfD.
- DfD of buildings is still in its primary stages and more effort especially with practical examples is required.
- The current precast elements are primarily designed for fast assembly where the end of life scenario still needs to be considered.
- Reuse of concrete elements is possible as long as they are in a suitable condition and they did not reach their technical life limit which is 300 years according to some estimations.
- Very little attempts to design demountable precast systems have been done; in addition to that these systems still need to be evaluated with regard to their disassembly potential.
- More advanced assembly technologies and machines that provide fast, safe and effective assembly are still required.
- One of the preferable aspects of concrete is its ability to provide different function for the building such as support, protection and appearance.
- Concrete buildings that have high standardization aspects should be designed for disassembly and transformation capacity due the variety of environmental benefits that could be obtained.
- The new developments in material technologies provide solutions to challenges and hindrances that may face design of concrete buildings for disassembly.

Chapter 2. Demountable building systems

Introduction

Demountability of systems is a sustainable aspect that allows change, replace and reuse, it also prevents from material loss and environmental pollution. In technology and especially automobile industry demountability cannot be avoided, it allows maintenance and upgrade of parts and components. Demountability has also been a norm of building processes for nomadic people who tend to continuously move for food and water. Again, recently demountability characterized a number of building types such as timber and steel buildings due to the features of these building materials metal and wood. This chapter reviews the classical demountable systems and shows their characteristics.

2.1 Children toys

A lot of children toys follow the concept of demountability and reuse. Some of these toys can serve for different designs and forms such as classic Lego and building blocks and some serve to build a specific model such as automobiles, airplanes and buildings. The main concept behind Lego games is the ability to construct a non-limited number of forms and designs by assembly and disassembly of building units. Every Lego unit has cylindrical projections studs on its top and tubes in the base which helps to fix the other units on the top of each other by the mean of interlocking and friction. Other children toys such as building blocks have a simpler concept of making forms and designs by just laying the blocks units on the top of each other. The resulted forms are stable by means of the weight of units only. A more complicated demountable children toy is the metal building set. This toy is based on the concept of fixing plates that have cylindrical holes with steel bolt and nuts that can be later disassembled. Another toy is the modular wood building pieces that provide the ability to build predesigned buildings or other designs. The modular wooden pieces are attached and fixed together by interlocking.

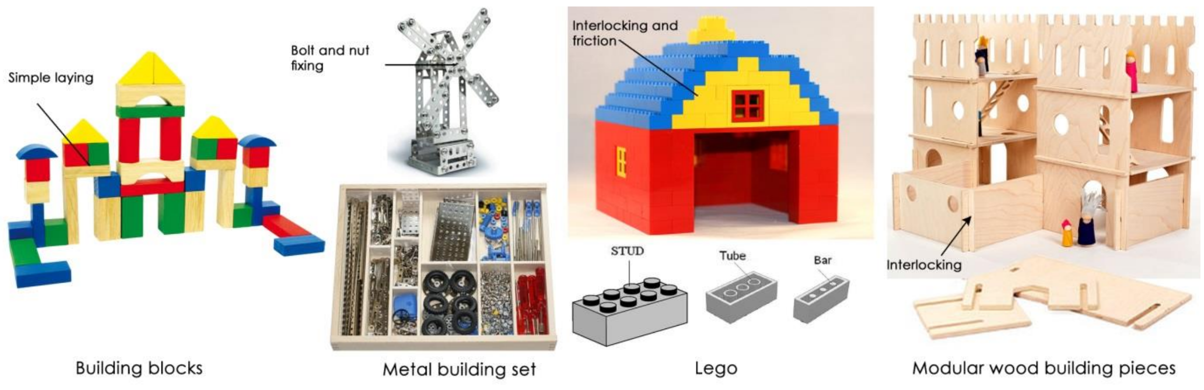


Figure 2-1: Demountable children toys.

These concepts provide the ability to build, demount and rebuild again and again. The same concepts have been applied in Architecture and furniture design. The concept of building block is existed in ancient Egyptian temples through dry stone construction and many other temples such as the Peruvian temples in Peru (Dry Stone Conservancy, 2015). Most of the mechanical services in addition to the facades made of metals have the same concept of metal building set where the assembly and disassembly depends on metal plates that are fixed by bolts and nuts. Some wall construction systems are assembled like Lego nowadays such as Q-bricks system. Dirk Althaus believes that when Architects and engineers want to design with prefabricated elements they need to keep Lego game in mind (Althaus, 2014) (see figure 2-2).

Figure 2-2: To the left: dry stone construction, to the right the use of Q-bricks (Georgievska, 2016), (Van Lier, 2014).

2.1 Demountable fasteners and buttons

In everyday life people use various types of simple demountable fasteners and buttons whether in clothes, furniture or equipment. The following sections show the most used ones and their working principles and potential use in architecture.

2.1.1 Fastening with Magnate

The power of magnate and its ability to fixing could be noticed through everyday use of house equipments and furniture. The permanent magnetic field provides a powerful tool to fasten things through the pulling force between the magnate and metal. It is always possible to demount the fastened elements by applying a force that is higher than the magnetic field. The power of the magnate can be calculated by pull force (Kgs) and it depends on the overall dimensions of the magnate material and the magnate contact area. See (Appendix 8) for some products and their pull force capacity. Figure 2-3 shows a pot magnate example (Lifton Magnates, 2017). The door is open for magnate applications in architecture especially when demountable connections are required for replacement, reconfiguration or reuse.

Figure 2-3: Round base - NB: multipurpose all-weather powerful pot magnet

2.1.2 Reclosable fasteners

Reclosable fasteners can replace the use of screws, bolts and other fastening traditional methods, when repeated operations of opening and closing, attaching and detaching are required. The working principle of reclosable fasteners is based on pliable loops on one side and stiff hooks on the other or dual lock system of interlocking stems (see figure 2-4). Most manufacturers nowadays provide a wide variety of closer and holding strength that suit various design applications. Such fasteners have been usually used intensively in clothes, but now it has wider range of applications both in furniture and architecture (see figure 2-5) (3M Company , 2011).

Figure 2-4: Two various types of closer fasteners construction

Figure 2-5: Various applications of reclosable fasteners in furniture and architecture

2.1.3 Rope tie

One of the most used demountable fasteners is the rope tie. This method is used for various applications from fastening elements to shoe tie. This method provides the ability to demount the tied connection just by pulling the rope which can be tied infinite times.

Figure 2-6: Classical shoe tie as a demountable connection

2.1.4 Zipper

Also called zip, fly, or zip fastener and known formally clasp locker. This device is used to bind the edges of a fabric or flexible material. In addition to its use in clothes it is also used in tents and sleeping bags. The working principle of the zipper is based on interlocking teeth and was invented by an American inventor called Whitcomb L. Judson (Friedel, 1996).

Figure 2-7: classical zip fastener

2.1.5 Snap fasteners

However snap fasteners are mainly made for dresses some types can be used for other applications with fabrics and other materials. The snap fasteners consisted of two interlocking discs made of metal. One of the discs is a circular lip attached to a disc that fits into a groove with fastening side rods that can be removed under certain pressure or pulling forces (see figure 2-8) (Ranvijay, 2014). The concept of snap fasteners could be used in architecture for fixing interior or exterior cladding when suitable fastening strength is designed.

Figure 2-8: Various types of snap fasteners

2.1.6 Releasable ties

Releasable ties are the developed form of non-releasable ties which are usually made of nylon or stainless steel. Unlike the releasable ties the non-releasable ties cannot be disassembled except by cutting the tie (see figure 2-9) (Kinglok, 2017).

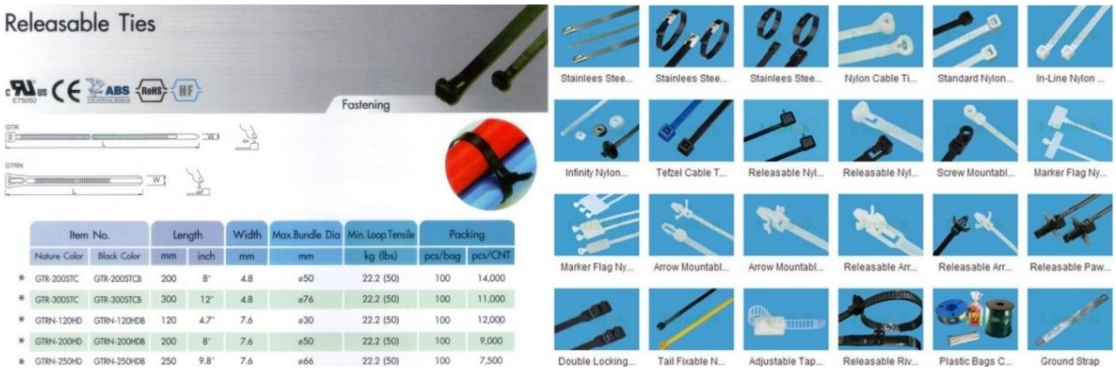


Figure 2-9: Various types of releasable ties and tensile strength

2.2 Demountable building systems

Building systems in term of construction materials could be classified into three categories: steel, timber and concrete buildings. The following sections discuss the steel and timber construction systems with regard to their components and connections demountability.

2.2.1 Steel building systems

Iron as a building material has been used before the discovery of steel, where it has been used as cast iron then wrought iron. The discovery of steel - which is an iron alloyed with small amounts of other elements such as carbon - and the production of various types that have various properties opened the door for multiple applications in buildings (Orton, 1988). Steel building systems vary according to the structural system which determines mainly the transfer of loads. The common steel building systems according to Allen and Iiano are: structural steel frame, trusses, arches, tensile structures.

The following sections are going to review and discuss components and connections and show their demountability potential.

2.2.1.1 Structural steel frame system

In the year 1883 the Home Insurance building was erected using structural steel frame. The use of steel frame at that time allows reduction of the thickness of load bearing masonry walls of traditional buildings. The skeleton frame is made of hot rolled section columns and beams to support the loads of the building and its components (Barry, 1966).

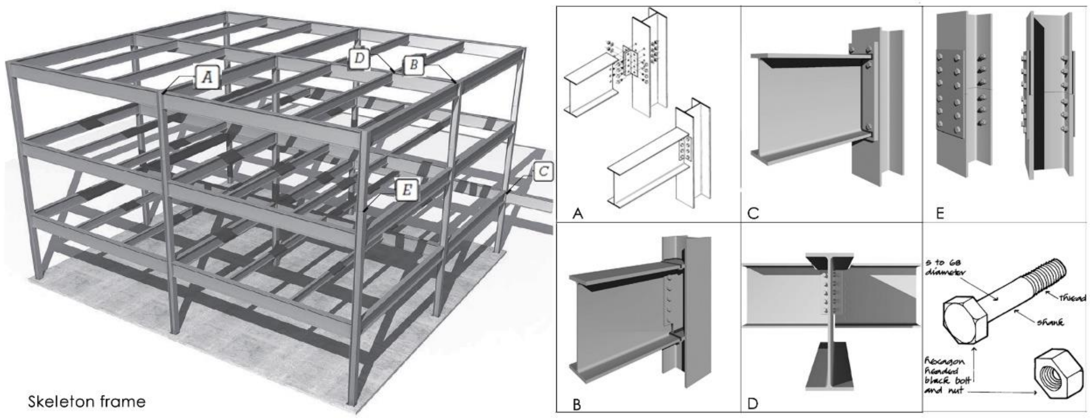


Figure 2-10: Skeleton steel frame and types of connections used between columns and beams (Allen & Iano, 2009)

Structural steel frame could be found in other forms than hot rolled section beams and columns such as pin jointed structural steel frame. After the second world war the shortage of materials and skilled craftsmen pushed the local authorities in England to develop standardized components for building systems which help CLASP [(1)] building system to emerge. CLASP building system retained the pin jointed frame as it was the cheapest light structural steel frame (Barry, 1966).

[1] : The Consortium of Local Authorities Special Program CLASP was formed in England in 1957 to combine the resources of Local Authorities with the purpose of developing a prefabricated school building program.

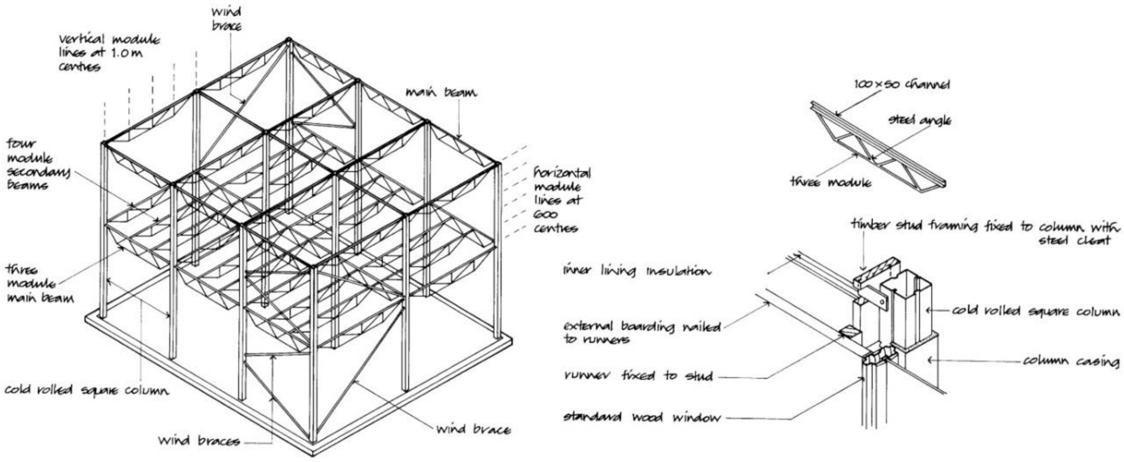


Figure 2-11: Pin jointed steel frame

- **Connections and fasteners**

Steel elements could be fixed together using different types of fasteners such as rivets, bolts and welding. While rivets and welding are permanent fasteners that cannot be reversed except by cutting, bolts provide the ability to demountability (see figure 2-12) (Allen & Iano, 2009).

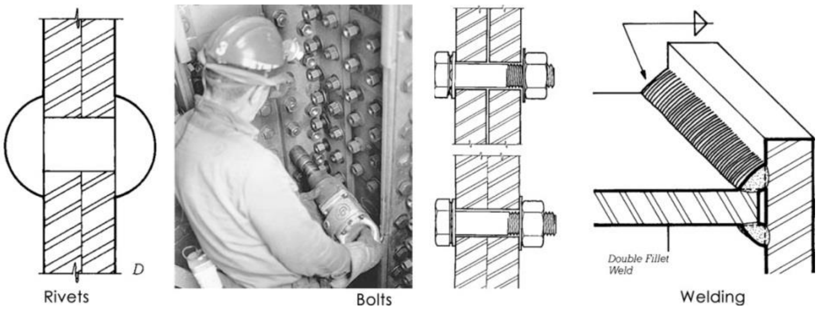


Figure 2-12: Types of steel fasteners

- **The crystal palace**

Despite the fact that some steel buildings emerged at the beginnings of the 1800s, the crystal palace of the 1851 was an iconic building. This can be attributed to the release of traditional building methods at the time architects was busy looking to the past with gothic revival and art and craft movement. In addition to that the design limitations of the large exhibition building 800,000 square feet and a limited budget made the building not only the largest that ever has been constructed but also the cheapest for cubic foot. Furthermore, the building needs to be demounted and removed from the site after the event.

Figure 2-13: The Crystal Palace as built (Bridgwater. Gloag, 1948)

The structural system

Josef Paxton designed the building to have modular components and cast-iron columns in two lengths. The girders were made of cast iron for their compression elements and wrought iron for their tension elements and were assembled in site using rivets. A 24-foot modular dimension was used with standard connectors. The cross section of the hollow core columns was increased when needed by increasing the thickness of the tube. The hollow core was used as drainpipe and the columns were fixed to column bases that rested on concrete pad footings by bolts. An inventive connection that relies on wedges was used to connect the girders with columns. The two-way flooring system of trussed beams was used to support the floor of the galleries with additional rafters and binders. The transept was covered by sixteen arched ribs made of timber and wrought iron. Flat timber planking built in three vertical layers and bolted at 4-foot interval was utilized for the arched ribs (Addis, 2006).

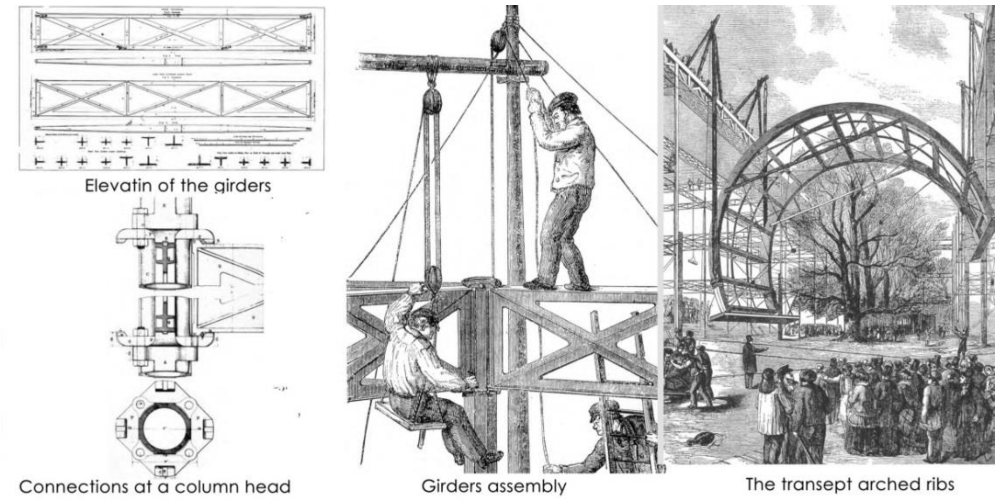


Figure 2-14: Structural details of the Crystal Palace building (Addis, 2006)

The building envelope

Ridge and furrow glazing supported on the inventive “Paxton gutter” were used to cover the roof for each bay which consisted of three spans. This system facilitates drainage of rainwater and condensation to transverse timber channel and then to the hollow columns. The vertical façades were constructed using timber sashes and resembled the cast-iron columns (Addis, 2006).

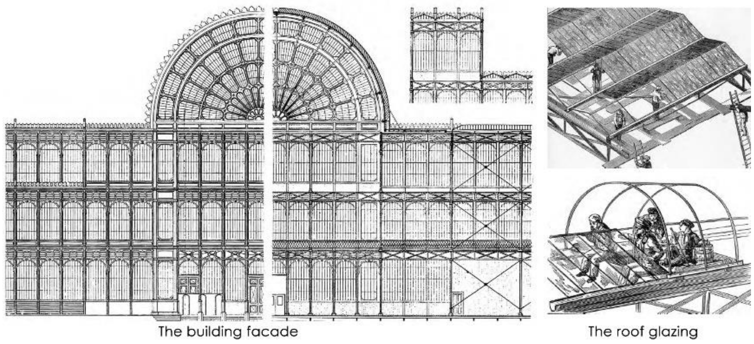


Figure 2-15: The façade design and the glazing of the roof indicates the use of modular components (Chadwick, 1961)

Lovers were also used in the facades for natural ventilation and were driven by rope and pulley that controlled manually from ground. “Buff calico” was used as external covering over the roof and the south-facing facade to reduce solar gain (Addis, 2006). The Crystal Palace was one of the first buildings that truly illustrate the physical building integration through various prefabricated building components and elements in all building levels. Durmisevic believes that it was a clear example that highlighted the technical composition of buildings (Durmisevic, 2010).

- **Richard J. Dietrich (Metastadt system)**

Richard J. Dietrich developed the “Metastadt” system as a response to the wrongly programmed urban development after the Second World War. The alternative metropolitan concept "Metapolis", later "Metastadt", was developed in 1965/66. A concrete utopia of the progressive metamorphosis of the traditional city to the "Überstadt" of tomorrow by superimposition with multifunctional variable and regenerative spatial structures. The desired recognition of this meta-city concept required the development of an entirely new design with new technical potentials through a manufactured industrial serial production construction system. This construction system should be planned to control the dynamically growing and changing structure. OKAL one of the leading construction company in Europe, and later also by the “Stahlbaukonzern” “Thyssen” - took the initiatives to finance and promote the first series-ready “Metastadt” construction system and several prototypical buildings realized over several alternatives in the years 1969-74 (Dietrich, 2017).

Figure 2-16: Metastadt construction system by Richard J. Dietrich

2.2.1.2 Trusses and Arches

Steel members are used to produce triangulated arrangements that are lighter and deeper than hot rolled beams or improved beams; they can span long distances and carry heavy loads. Steel truss members could have various section shapes such as L-shaped angels or tubular-shape.

Figure 2-17: Various types of truss and arch steel systems (Allen & Iano, 2009)

These members are connected together using either welding or steel connections. Steel truss are available in simple form or space frame which extends to the third dimension caring the load by binding in two directions. Arches structures can be made by binding slandered wedge-flange shapes or by jointing plates and angels to form a cylindrical roof vaults or spherical domes.

- **Connections**

Steel connections in general are made either by welding or pins and bolts. Special connections could be designed to provide the truss with aesthetic appearance and demountability when bolts are used. The following figures show different types of connections depending on the section shape of the truss members.

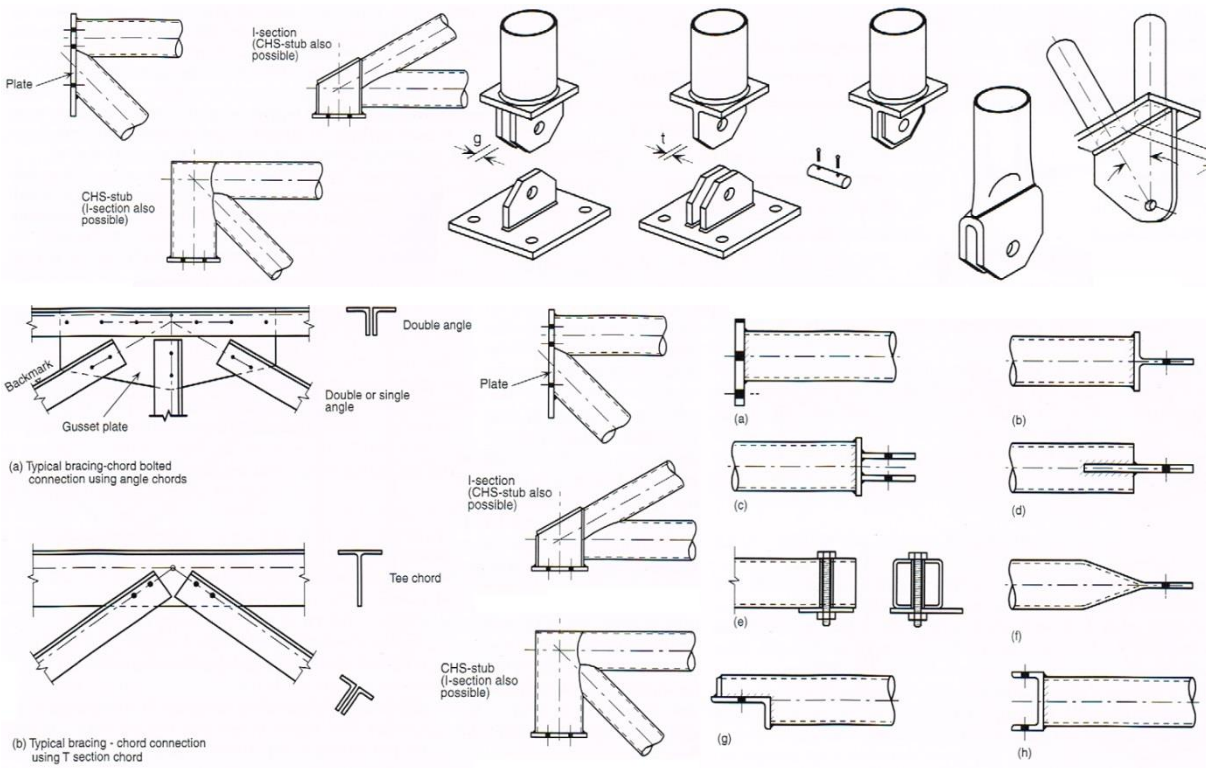


Figure 2-18: various types of steel truss connections mainly for simple truss (Trebilock & Lawson, 2004)

The following are various types of space frame connections that allow multiple attachments at every joint of the steel space frame.

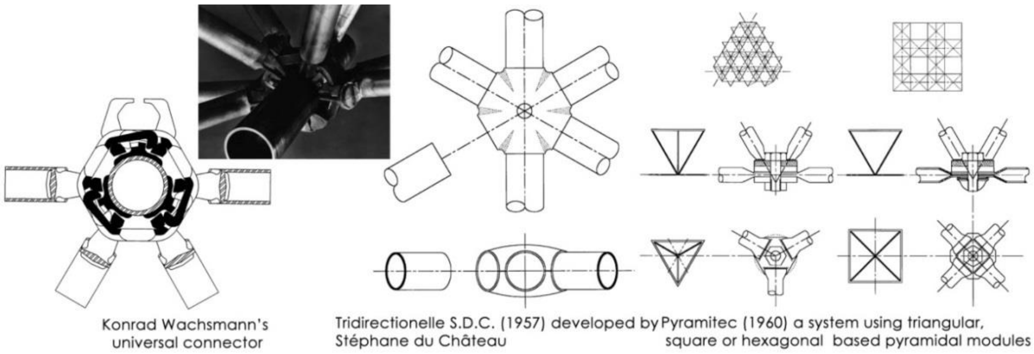


Figure 2-19: various types of steel space frame connections (Chilton, 2000)

- **Konrad Wachsmann**

Konrad Wachsmann is a German-born and education American architect and designer. He is well known for the contribution he made to mass production of building components. When Wachsmann moved to the U.S. he worked with Walter Gropius until 1948 and established the General Panel Corporation which was a leading company in the production of prefabricated buildings components. In 1950 he and his partners in the department of advanced building research designed a construction system for large aircraft hangars using prefabricated parts. The most notable work of Wachsmann was the city hall, California City in 1966. One of his interesting writings is "The Turning Point of Building 1959" in which he insisted that technology and art are inseparable (Encyclopædia Britannica, 21017).

The museum of modern art once wrote about Wachsmann that his new type of construction at that time was based on two original inventions. The first is a "Mobilar" tube joint which facilitate the assembly of tubular members without riveting and hand-welding and easy extension and modification. And the second is a mobile wall unit which provides the ability to completely removable doors (Museum of Modern Art, n.d.).

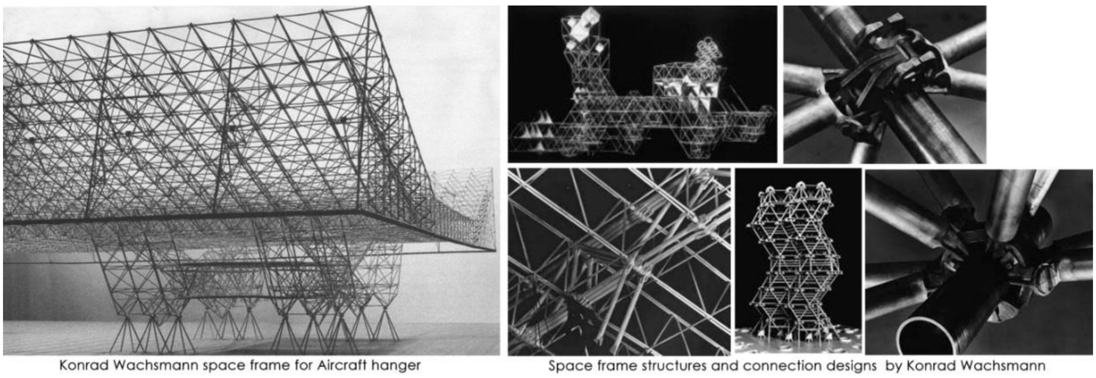


Figure 2-20: Various work of Konrad Wachsmann (WIGLEY, 2001)

- **Buckminster Fuller**

R. Buckminster Fuller is an American design scientist and practical philosopher. He dedicated his life to solve global problems in housing, shelter, transportation, education, energy, ecological destruction and poverty. Fuller was interested in improving shelter, he realized that applying modern technology in shelter construction will make shelter more comfort, efficient and more economic. It will also facilitate solving shelter problems and help people to live in a better condition. Fuller words “more with less” always motivates architects. The following are some of his inventions:

Geodesic domes

Fuller interest in nature and its creativity pushed him to study the shell structure and invent a number of alternatives that are less expensive, lighter and stronger than traditional shells of timber brick and stone buildings. The use of tension instead of compression was possible to Fuller as a new material such as steel was available. Fuller noticed how the difference in the geometry of rectangle and triangle when applying pressure to each structure will make the triangle withstand the pressure while the rectangle fold up.

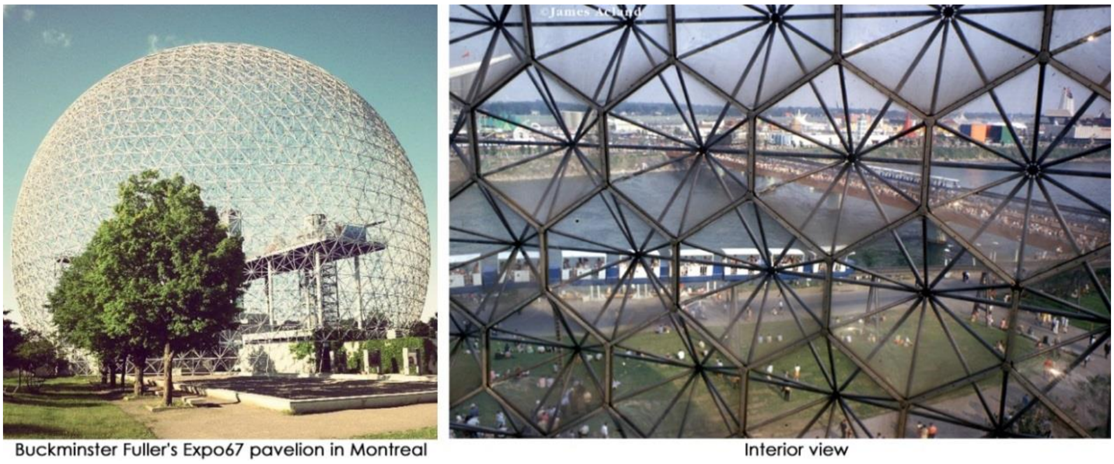


Figure 2-21: The geodesic dome of Buckminster Fuller in Montreal (Frankkuin Instagram, 2013), (James Acland)

The previous notice directed him to design an architectural geodesic dome depending also on his idea doing more with less. Fuller realized that when a spherical structure is created with triangles, it would have unparalleled strength (Buckminster Fuller Institute). One of his famous structures which has been constructed with geodesic domes is the U.S. pavilion for Expo ’67 in Montreal, Canada. The diameter of the dome was 76 m and it was a three-quarter sphere with double layer tubular steel grid. The dome designed to have a triangular geodesic grid for the outer layer and a hexagonal grid for the inner (see figure 2-21) (Chilton, 2000).

Dymaxion House

In 1920’s Fuller designed a house solution for mass production. He believes that this design should be affordable, efficient in terms of environmental context and can be easily transported.

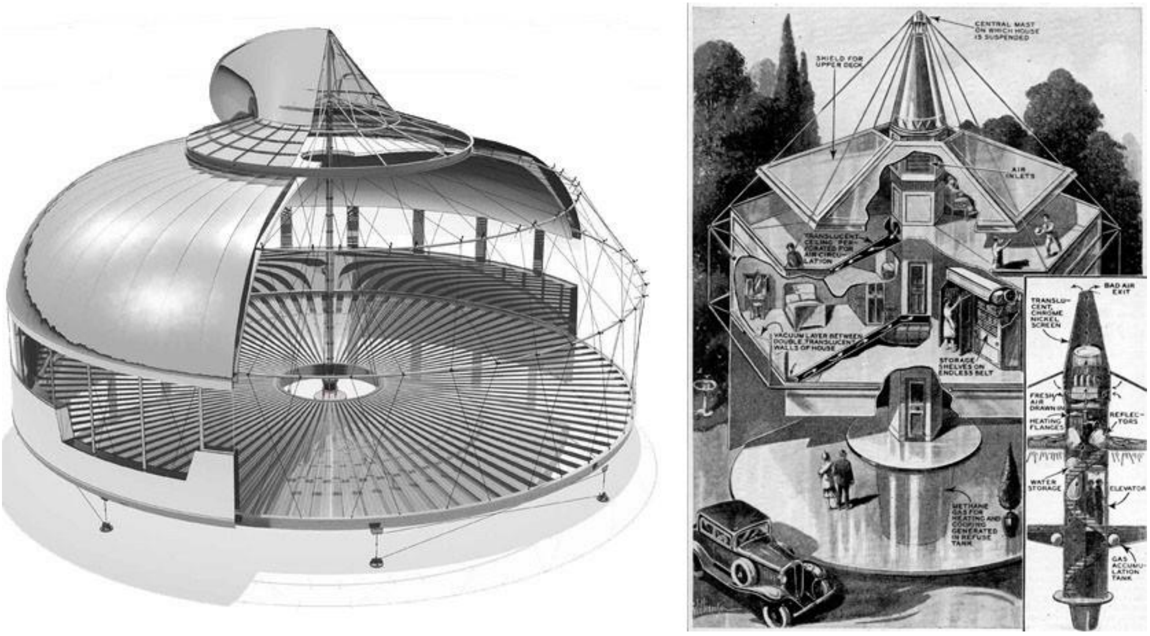


Figure 2-22: The dymaxion house of Buckminster Fuller concept and structural system (Adrian, 2016)

The design of the dymaxion house was not built until 1945. The word “Dymaxion” stands for three words that affected and inspired Fuller: dynamic, maximum and tension. The structural concept of this house was based on tension suspension from a column at the center of a cylindrical form. Fuller’s house was made of engineered material that is weather-resistible. The house has a natural heating and cooling system and it was storm and seismic resistant (Buckminster Fuller Institute).

- **Max Mengeringhausen**

Max Mengeringhausen is a German engineer. He worked in providing innovative and customized solutions for the construction sector by developing industrial prefabricated elements "**ME**ngeringhausen **RO**hrbauseise" (tube/node construction) in the late 1930's. He developed a wide range of construction elements as packages or part-key solutions based on his philosophy of transferring natural laws into construction technology (MERO-TSK International GmbH & Co. KG, 2017).

Many projects around the world have been built using the MERO systems especially those of free form geometry such as Heydar Aliyev Merkezi Project, Baku by Zaha Hadid and Ferrari World in Abu Dhabi. Mero systems involved developments of various connections that facilitate the construction of such free form geometry. The most common Mero systems are:

Node Connectors for Double Layer Free-Form Structures

The connector for double layer structures is the classical ball node connector (see figure 2-23). Also cladding elements can be connected to the ball using point supports such as spider connector with rotules to fix glazing elements. The ball node has a bowl node connector as a complementary element in double layer structures. It allows the use of structural members with prismatic cross sections in the outer layer as a direct support of cladding members (Stephan et. al , 2004).

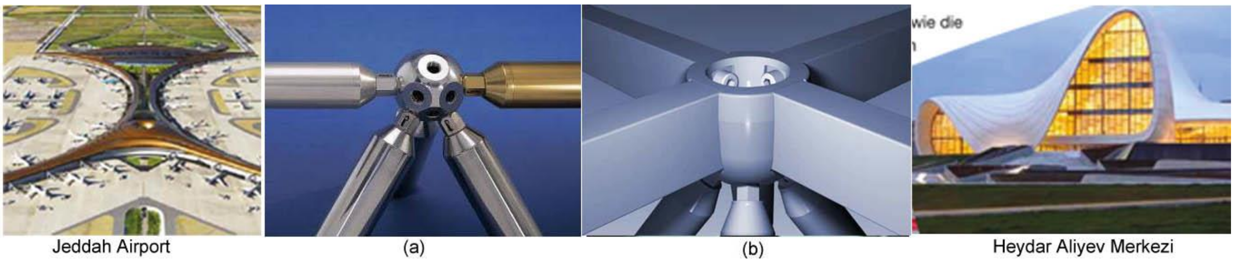


Figure 2-23: Node connector for single and double layer free form structures

Node Connectors for Single Layer Free-Form Structures

Single layer structures provide a tool to present the architectural partiality for transparent building envelops. Connectors for single layer structures can be categorized into two main groups: splice connectors and end-face connectors (see figure 2-24, figure 2-25).

Splice connectors are characterized with “The contact surface between the node and the connected structural member runs along splice plates in the longitudinal axis of the member” and the fixing can be recognized as bolted splice with shear-stressed bolts or welding(Stephan et. al , 2004).

Figure 2-24: Various types of splice connectors

End-Face connectors are characterized by “The contact surface between the node and the end-face of the connected structural member is transverse to the longitudinal axis of the structural member” and the connection can be recognized as an end-plate connection with tension-stressed bolts or by welding (Stephan et. al , 2004).

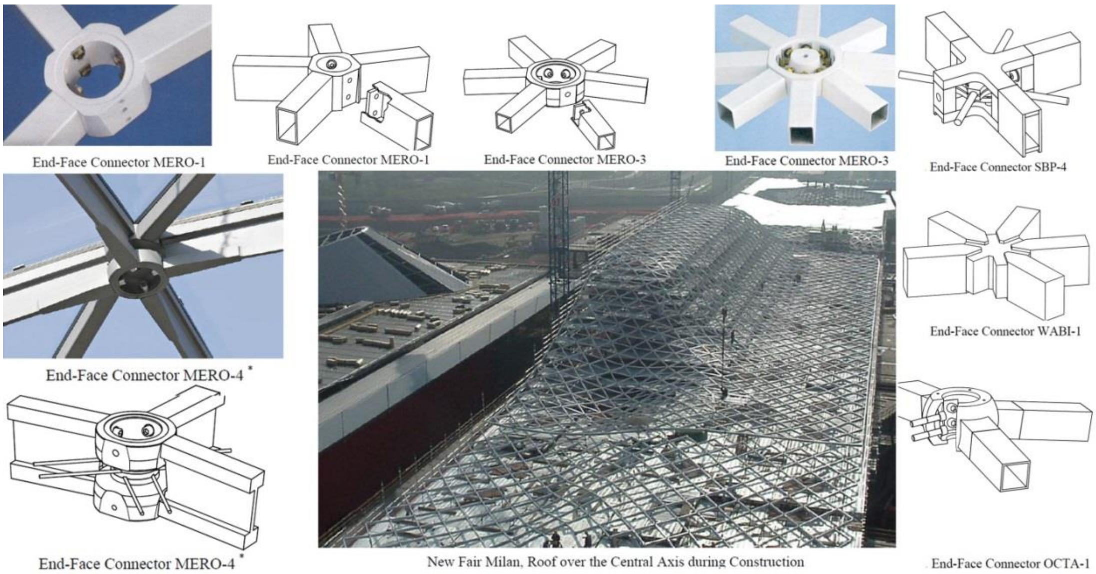


Figure 2-25: Various kinds of End-Face Connector

2.2.1.3 Tensile structures

These types of steel structure represent suspended or "tent-type" structures, where the main elements are those elements that have been designed to carry the loads. These types of structures are more explicit in architecture and their connection details are more complex than other types of steel structures. When designing tensile structures care should be dedicated to the load paths, stability, cladding interfaces and foundation design. Tensile structures usually utilize tubular sections for the supporting members that are connected to the attachment of the ties at their top. The design of tension attachments, their form and complexity depends on the forces transferred, the number, size and orientation of the individual ties (Trebilock & Lawson, 2004).

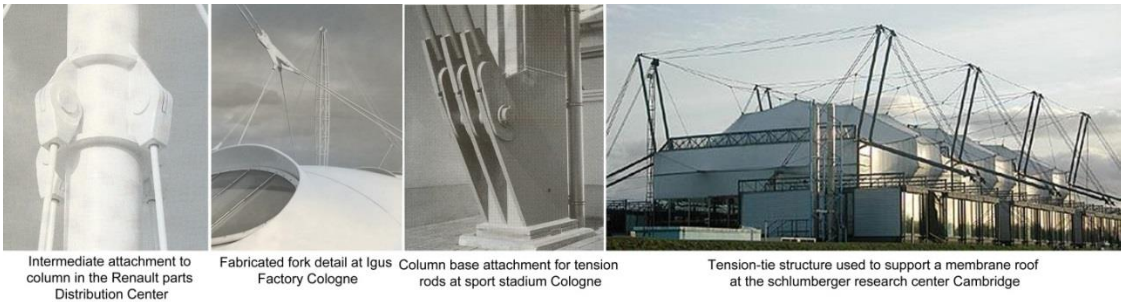


Figure 2-26: Tensile structures and various types of tension attachments

- **Tie rod or cable connections**

Two types of connection are usually used in tension structures that use tie rod or cable connections:

1- Connections between tie rods or cables and main structural elements

2- Connections that connect tie rods or cables to each other's.

Both of these types of connections need a way of adjustment that prevents sag in members and to induce a specific tension. Various forms of end details and fittings for connections utilize stainless steel components such as:

1- Cable terminations

For high-tensile forces ropes and wire cables are used nevertheless their ends cannot be traded or welded. A number of methods could be used in this case such as socket termination and the swaged (Trebilock & Lawson, 2004).

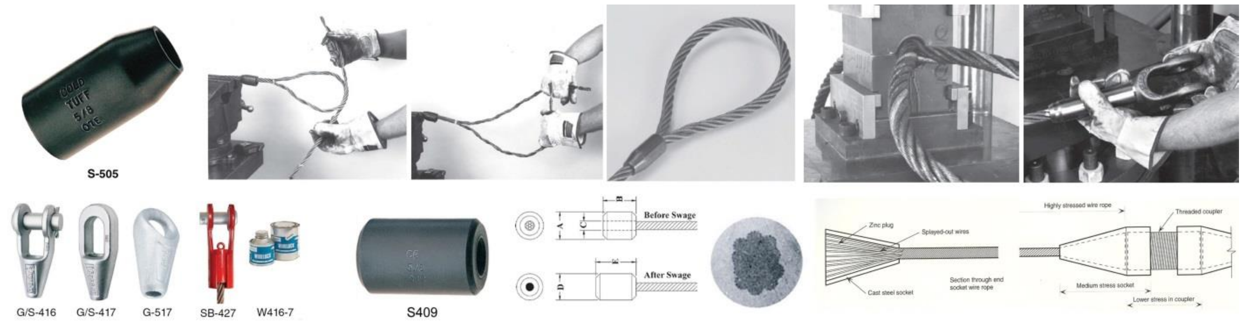


Figure 2-27: Various types of socket and swaged terminations

2- Tension bars

When tie based the connection could be made by threading the bars where thread is not cut but is rolled on to the bar. This method allows reduction of any sag in the rod to provide efficiency (see figure 2-28).

3- Fork connections

These connections are used to connect more than one tie to a single node point; usually the fork is attached to a rod and not directly to the main member which simplify their fabrication. Pinning rather than bolting is sued for fork connections for quick assembly at site (see figure 2-28).

4- Pinned connection

Pinned connections usually used to connect a rod to a plate. In most cases the design of these pins takes into consideration emphasizing the pin form by using flatter coupling and larger pins (see figure 2-28) (Boake, 2015).

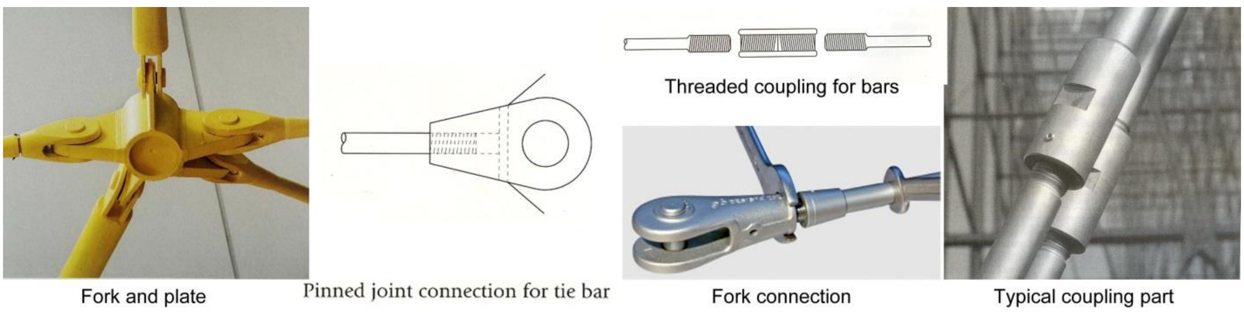


Figure 2-28: Various types of cable connections

2.2.2 Timber building systems

Wood has been used as a building material since the antiquities, since trees were available in all times. Wood is one of the most building materials that fulfill the sustainability of buildings and resource efficiency. The characteristics of wood make it a favorable building material; it has a considerable tensile and compressive strength and relatively light weight with considerable load bearing capacity (Ruske, 2004). Wood has an intermediate sound and heat conduction; it has a good steam-diffusion that decrease with humidity increase. Over-dimensioned wooden structural elements can resist fire for about 90 minutes. Humidity should be considered when designing with wood since it tends to deteriorate timber elements when longitudinal cracks occurred because of difference in shrinkage between the inner and outer layers. 30% humidity of (mass present) usually found in fresh building wood which should be decreased by drying to 20% in order to be ready for use. In warmed spaces the average humidity of wood is 6-12%. It is not possible to avoid cracking in the wooden elements but these cracks do not affect significantly the stability of the structure (Althaus, 2014). Cut wood is usually used for piles, pillar, beams and ceilings. The one-direct feature of timber elements requires to be assembled to the surface by addition from large elements to smaller. Nails were the common way of connecting timber elements together, but nowadays steel connections are used instead. In addition to normal cut wood other methods of shaping timber elements from wooden material are existed such as: industrial glued wood which can be formed by connecting wooden pieces with glue to make beams and panels and wood as additive material when wood is shredded and compressed with glue (Althaus, 2014).

2.2.2.1 Nomadic tents

The tent is one of the earliest forms of nomadic shelters. It varies in form place to another according to the environment and culture. Tents have been used in various climates from deserts to frozen arears around the world. The tent appearance varies as it is affected by factors such as the environment, the available construction resources and the use. It can be said that tent is a general term that call light-weight and transportable building and distinguished by flexible membrane as a skin. The structural solution of the tent came as a response to the need for light-weight elements that could be easily dismantled and transported. The tent utilizes the tension forces to extend the very thin membrane over a long span with the help of few compression loaded supporting poles to resists considerable loads. The most common forms of tents could be noticed in figure 2-29 (Giller, 2012).

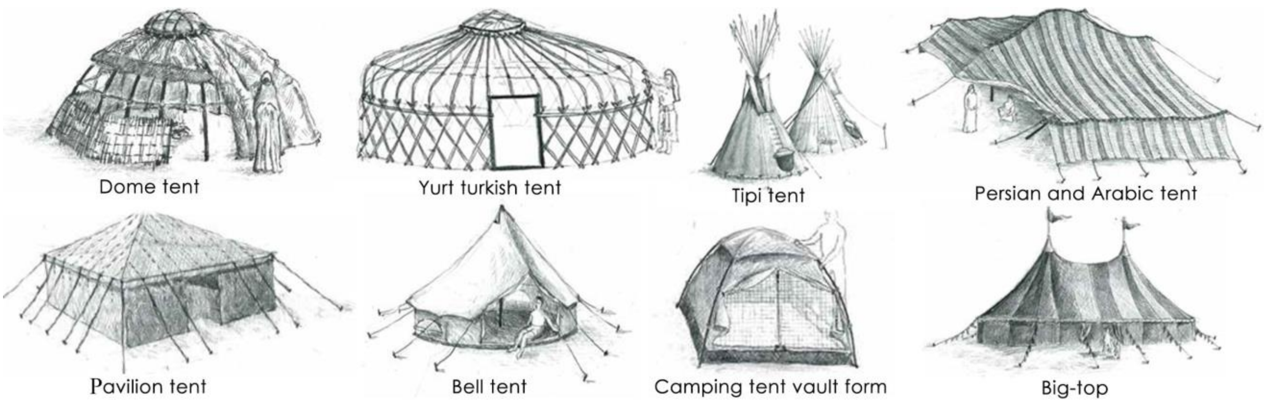


Figure 2-29: Some of the common forms of nomadic tents

- **Structure of the tent**

The structure of the tent depends on the tent form which is generally a simple geometric form such as cone, cylinder or dome. The common form is based on a circular plan and a roof made curved as a tensile structure. The circular shape ensures stability and minimizes the surface area which provides light weight and simplicity. The tensile forces define the shape and structure of the skin or rope that supports frameworks and shape the form of the skin. Giller distinguishes between two types of tents: frame tent and skin tent (see figure 2-30) (Giller, 2012).

Figure 2-30: (a) skin tent, (b) frame tent

Connections and components

In nomadic tents ropes have been used mainly to connect the loading supporting poles or to provide tension force to suspend the skin. Dowels were used to fix tension ropes to the ground to provide the required shape and strength. And compression poles were fixed to the ground by digging deep holes that insure stability. Disassembly of these components was a simple process due to the light weight and simplicity of connections and components (see figure 2-31).

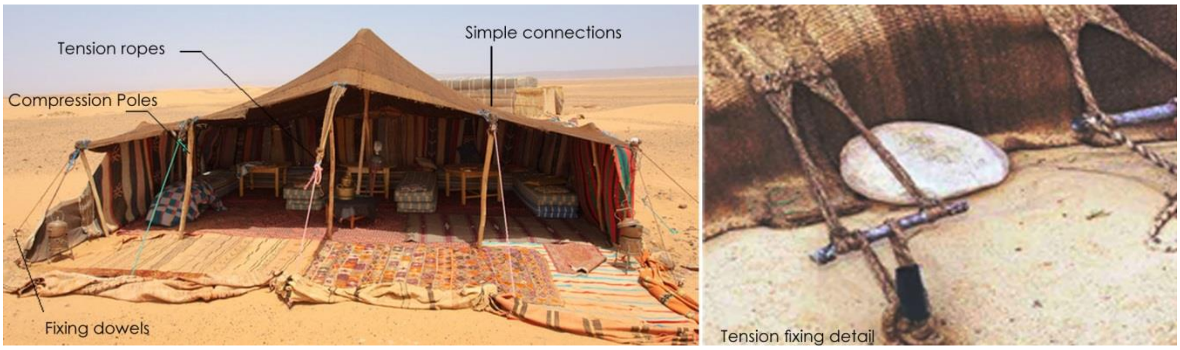


Figure 2-31: Component connections of tent construction

Modern designs and construction

The same concept of nomadic tents has been used in the production of modern prefabricated tents that make use of the new lightweight materials and prefabrication technologies. Such tents still have their important function in landscape and other architectural functions (see figure 2-32).

Figure 2-32: Modern tents and their prefabricated connections and components

2.2.2.2 Classic methods of timber construction

A number of timber construction methods could be found around the world. These methods of timber construction represent six main timber systems that differ in structural integrity and organization of elements. These systems according to Ruske are:

1. Log construction
2. Traditional timber frame (half-timbered) construction
3. Balloon frame construction
4. Platform frame construction
5. Skeleton frame construction
6. Panel/ Plate construction system

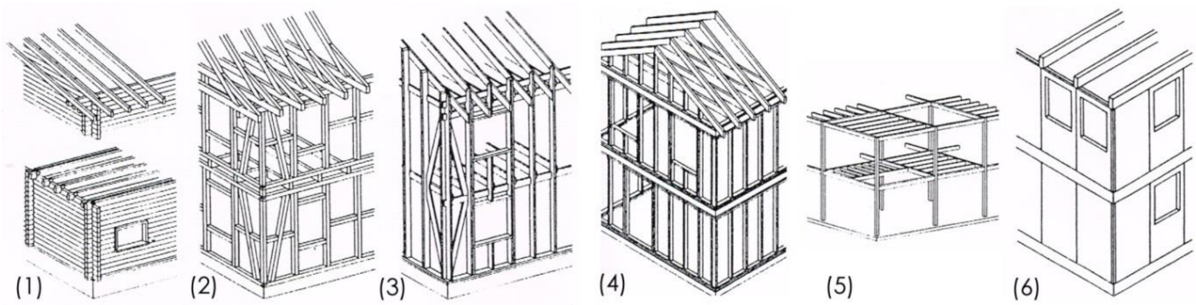


Figure 2-33: The common classical timber construction systems

- **Log construction system**

Log building system was used for various building types up to five storeys high. One of the distinguishing construction characteristics of this system is the interlocking corner connections. The concept of tongue and grove is used to connect softwood beams or logs of various profiles. Glue is used to improve stability of the beams and walls (Ruske, 2004).

Figure 2-34: A log timber construction house

- **Half-timbered construction system**

This method of construction has widely spread in central Europe and still used due to the development of computer-controlled processing machines that is able to produce the connections and joints precisely and economically. In this system the assembly of elements is occurred storey-by-storey where the corner of the buildings should have struts to transfer the wind loads to the sole plate. Various materials could be used between the supporting timbers to enclose the building envelope. However, the traditional method of enclosing the walls do not provide the building of the required thermal insulation, so a layer of cladding with insulation could be used either inside or outside. Tenons and notched connections were usually used for this rigid frame system, but the development of modern steel connections helped in simplifying the assembly of joints and provided future ability for disassembly (Ruske, 2004).

Figure 2-35: Half-timbered house construction for the first and second storeys

- **Balloon frame system**

In this system the vertical timber elements continue from the ground upward to two or more storeys. This system is known in North America but not in Europe. As in the half-timbered system struts should be used at the corner of the building to satisfy stability under wind loads (Ruske, 2004).

Figure 2-36: Balloon frame construction

- **Platform frame construction system**

This system is widely used in North America where buildings up to eight storeys in height could be built. As in the traditional half-timbered system the assembly is done storey-by-storey. In this system the external cladding contributes to the solidity and stability of the building. This system has a simple construction principle where storey-height or timber vertical elements are placed at small distances about 62 cm and fixed with the sole plate and the wall plate from above which form the wall frame.

Figure 2-37: Platform frame construction

This frame is combined from both sides with sheeting made from plywood, OSB or chipboard, where the insulation is added between the sheeting. Nailed connection and standardized elements are used in this system. In this system also cladding is required (Ruske, 2004).

- **Skeleton frame construction system**

In this system the structure is characterized by openness. The wall could be either wide glass areas or other material. The structure in this system depends on load bearing columns and beams which can span up to eight meters. Glue is used for the laminated elements to provide stability and stiffness (Ruske, 2004).

Figure 2-38: Skeleton frame construction system

- **Panel/ plate construction system**

Depending on the principle of frame building timber, panel elements are prefabricated at the factory and brought to the site ready for assembly. These panels are usually produced in the size of the wall insulated and sheeted, doors and windows are also integrated to the panels at the factory.

Figure 2-39: Panel/ plate construction system

2.2.2.3 Engineered timber construction

Engineered wood provides the ability to produce large elements by combining smaller parts. The concept of engineered wood includes reassemble of small sticks using adhesive and pressure to produce new manufacture element that has higher value and less variability of the sum of its parts. The produced engineered element has big benefits such as the reliable structure performance and consistency. Engineered wood elements are characterized by the removal of defects and the consolidation of strength. These elements could be used for various architectural and structural purposes such as walls, floors, columns and beams. A number of engineered systems using adhesives and glue could be distinguished such as:

1. Glue-laminated timber (glulam)
2. Laminated veneer lumber (LVL)
3. Laminated strand lumber (LSL)
4. Parallel strand timber (PSL)
5. Cross-laminated timber (CLT) (Mayo, 2015)

(1) (2) (3) (4) (5)

Figure 2-40: Glue based engineered wood systems

In addition to the previously mentioned glue based engineered systems other non-adhesive-based solid wood systems could be produced such as nailed laminated elements and dowel Laminated elements. In these systems nails and dowels are used to fix the traditional solid wood elements (see figure 2-41) (Mayo, 2015).

Figure 2-41: Nailed and doweled laminated elements

2.2.2.4 Design of timber joints

To make a system from timber elements it should be connected and jointed in a proper way. The structural behavior of the system most of the time is affected by joints design. These joints provide the structure with moment stiff connection or hinges. Joints design also affects the overall economy in a building system. They can be classified into three groups according to Eric Borgström:

1. Tradition timber joints: were used in traditional construction before the emergence of steel dowels and details. These joints should be strong enough to provide stability. The load transfer through these joints is limited (see figure 2-42) (Sobon, 2004).
2. Dowelled joints: these joints are the most common type, they transfer loads through shear in mechanical fasteners and can be designed to support ductility, these joints include the use of: nails, screws, dowels,

nail plates (in combination with anchor nails/anchor screw) and punched metal plate fasteners and bolts (see figure 2-43) (Borgström, Eric;, 2016).

3. Glued joints: including the previously mentioned systems

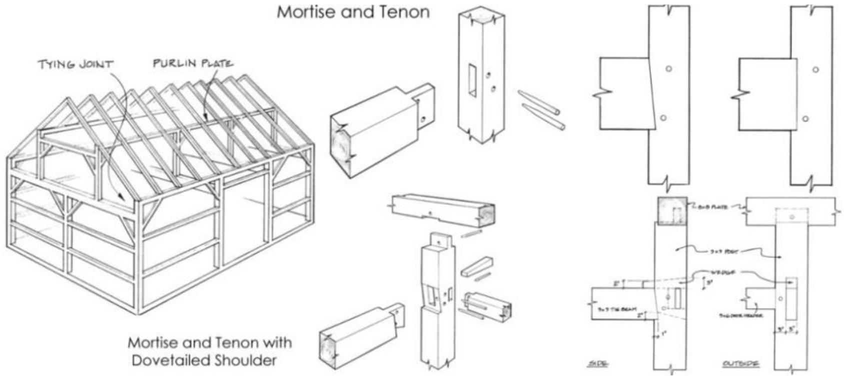


Figure 2-42: Traditional mortise and tenon connections

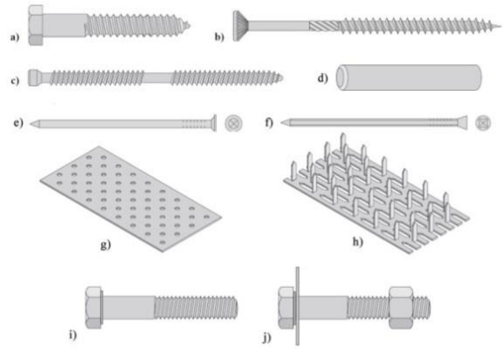


Figure 2-43: Various types of steel fasteners for timber joints

2.3 Conclusion

It can be concluded that the steel and timber buildings in general have two main sides that affect their demountability: these sides are connections and component design. From the previous review of the various types of steel and timber buildings and systems the following characteristics can be concluded.

2.3.1 Characteristics of demountable buildings

It is clear that connections in steel and timber structures have a great impact not only in the structural stability and precise of the building but also in the architectural aesthetics. Connections are mainly used to connect elements of different orientations and sizes. In general these connections can be categorized into two categories regarding their demountability: demountable and not demountable. However cutting is possible for non-demountable joints, this process require energy and cause other environmental impact.

2.3.1.1 Demountable connections

1. These connections despite their forms can be disassembled by release of nuts and bolts for steel connections and spigots or screws for timber. When rivets are used for steel connections these rivets

can be disassembled by breaking which will free the attached members. When nails or nail plates are used disassembly normally cause defect to the connection. The same when welding is used for connecting steel elements: disassembly of connections requires cutting which is not a preferable disassembly process.

2. In most cases access to connections is possible due to the exposed nature of joints for architectural aesthetics.
3. In general, these steel connections can be classified as direct connection with additional fixing device and this type has a good disassembly potential.
4. These connections have very high tolerances due to their precise production.

2.3.1.2 Demountable components

In steel structures the design of components has a great influence on their demountability. In general components of demountable steel buildings have the following characteristics:

1. These components can be functionally decomposed through functional separation and functional dependence.
2. These components have clustering of materials and elements according to functionality.
3. There is a base element that works as intermediary between systems and components.
4. Long life-cycle elements are assembled first then the shorter following by the shorter.
5. These components have a vertical position of relations in relational diagram of the building systems.
6. These components can be assembled in a parallel assembly.
7. These components have geometry of element edge that is open or symmetrically overlapped.
8. These components are standardized and premade.

Chapter 3. Concrete technology and building systems

Introduction

During the last centuries no change has occurred to the concept of building due to the limited resources and technologies. In most cases buildings were being built to last for the lifetime as no substantial change was observed in the aspects of life that require altering the concepts of building and construction. After the industrial revolution and the emergence of new materials and technologies the consumption of resources has been increased. Also, aspects of life have started to change as a respond to the newly emerged technologies. The continuous change in the aspects of life now required a new type of buildings that respond to change. From here the concept of building needs to be reconsidered. The way in which we assemble our buildings needs to be revised to include the potential for change, adaptability and reusability. This chapter discusses the construction and assembly of buildings with a focus on concrete and its technology. It tries to find links between the developments in the concrete technologies and the end-of-life scenarios to substitute demolition with disassembly and reuse. This chapter also discusses the life-cycle of concrete as a building material and shows how the liner life-cycle model puts extra pressure on the consumption of resources and energy and contaminates the environment through solid waste and other contaminants.

3.1 Assembly and construction of the concrete buildings

The construction method of a concrete building decides its end-of-life whether demolition or disassembly and reuse. Building methods in which concrete is poured at the site to generate monolithic entities of columns, beams and slabs lead to one end-of-life scenario of the building the demolition. This can be attributed to the complexity and high costs of the disassembly process. Other building methods in which precast concrete elements are used allow disassembly of elements, however, some damage could occur when the connections are dismantled. Understanding of the aspects that affect the construction and assembly processes of concrete buildings required awareness of the roles and limitations that govern these processes. Also, knowledge of the capabilities of concrete technologies is required. In most cases concrete as a building material provides the building with some functionalities and the other functions need to be satisfied by other types of materials. Concrete buildings are distinguished from other buildings by the dominance of concrete. Concrete provides the building with different functions in all physical levels of the building such as load bearing, enclosing, protecting and the architectural appearance. This section shows how buildings are assembled and what aspects affect the assembly and disassembly process.

3.1.1 The role of basic and universal materials in building and assembly

Buildings are built using different materials, these materials are combined in a way that provides stability and functionality to the building. The same material could exist in more than one physical level and could have different functions. Figure 3-1 represents an assembly of a building and show a single level of the enclosure hierarchy (Habraken, 1998, pp. 96-98).

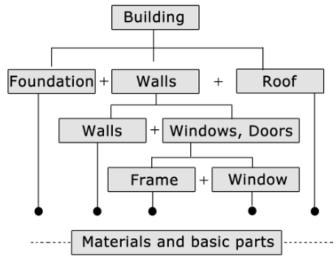


Figure 3-1: Assembly diagram (Habraken, 1998)

Because buildings are made of basic parts and materials those basic parts and materials could be existed in more than one environmental level. Cement blocks for example could be used at the enclosure level such walls and roofs as well as in fences and landscape elements. Referring to Habraken assembly diagrams it can be noticed that the bottom of the assembly hierarchy of building as well as the surrounding built environment are consisted of basic and universal materials at every level. These materials such as masonry, timber, ceramic tiles, sand, cement, steel, glass, plastic and gypsum play its distinct role and do its function of control and transformation (Habraken, 1998, pp. p.87-95). What distinguish a concrete building is the dominance of concrete as a construction material that satisfies various functions such as load bearing, enclosing, protection and appearance.

3.1.2 Dominant aspects that affect the building and assembly process

According to Habraken, the act of building represents an exercise of control over form. Parts are combined to form wholes. The wall for example is made by combining bricks and the building is made by combining walls, roof and floors which are the subsystems of the whole building. The assembly of these parts can be reflected through the part/whole hierarchy while the breakdown of the building shows dominance hierarchy. Such dominance can be noticed in a (wall – foundation) relationship. The dependence is caused by gravity, so gravity required a kind of sequence in which higher level is built first. Habraken discussed the role of gravity in the assembly chain and showed that a chain of dominance represents by foundation, walls and roofs due to the gravity demands.

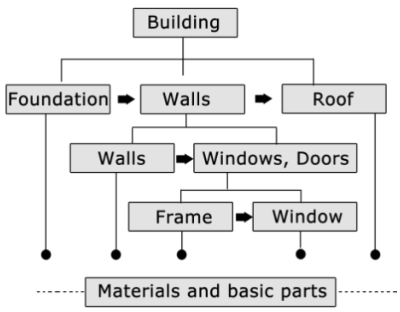


Figure 3-2: The building process arrows and assembly hierarchy indicates a dominance-dependence relationship (Habraken, 1998)

Figure 3-2 shows the process of construction in which foundations is constructed before walls, work made upward in the assembly chain until the level of construction is completed, work then descend again and goes upward till the completion of the second level and so on.

Habraken also showed that what determines a level is not the use of certain parts but the way of arranging form. As an example, he sees that the equipment joints the infill chain has its frequency of change and ultimately it is a part of another level. These levels of partitioning and infill ought to be separated in the building chain to represent the emancipation of parts to facilitate the construction (see figure 3-3). Habraken argued that in addition to gravity, the enclosure of form is another aspect of dominance (Habraken, 1998, pp. p.96-98).

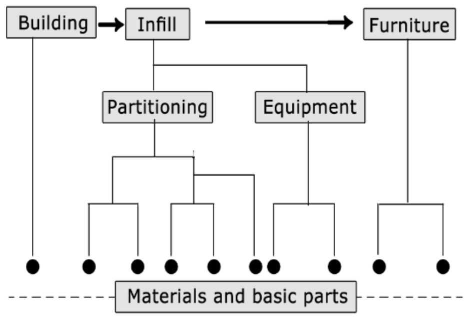


Figure 3-3: Assembly diagram for equipment as a level of the infill system (Habraken, 1998)

In addition to the previously mentioned aspects that affect the assembly of buildings, the author sees that technology also plays a significant role. Technology always connected to the invention and involved materials sciences, construction site properties and inventions in architectural technologies which are always in progress. Architecture technologies can be categorized into two groups: structure and form and climate and shelter (Silver & McLean, 2008, pp. p. 10-11). One of the main materials that distinguish the modern construction and technology is concrete. The following section presents the most developments in concrete technology and discusses how these developments could participate and add values to the concept of designing concrete buildings for disassembly.

3.2 Building with concrete

Since the invention of Portland cement in 1824 by Joseph Aspdin concrete has become the most used building material around the world. Concrete is produced by mixing materials such as aggregates and water with cement. When hardened, concrete become adamant and resistant to compression. On the other hand concrete is fragile in tension: so steel bars are used to improve concrete performance in resisting tension forces making what is called reinforced concrete. These structural properties together with the relatively low cost compared to other materials made concrete a superior building material. Concrete is used in two primary states to construct buildings: cast-in-situ and precast. In both cases ready mixed concrete is poured in forms and compacted to mold it within the forms around the reinforcement (Portland cement association, 2017). Precast concrete is usually manufactured at factories in a controlled environment and when ready parts and components are moved to the building site by trucks. Most of the precast systems depend on cast-in-situ concrete for connecting their parts and elements. This system is referred to by hybrid system. Many technologies and improvements have been applied to concrete to increase its performance such as additives, fiber reinforcing as well as post-tensioning and prestressing. Concrete which is poured in an initially liquid form has the ability to take any form, so appropriate formwork is made using a wide variety of materials such as plywood, steel, fiberboard and so on (Sandaker, Eggen, & Cruvellier, 2011, p. p.91).

It can be noticed that the end-of-life scenario of the concrete buildings has shown domination of demolition, however, some examples indicated that the reuse of concrete elements is possible when the building is constructed using precast concrete elements. This confirms that prefabricated or precast concrete is the suitable type that should be considered to be designed for disassembly.

3.2.1 Concrete technology

Cement, sand, aggregate and water are the main components of a concrete mix. These components are mixed in carefully controlled quantities to provide the desired strength and performance. The existence of water together with cement makes a chemical reaction called hydration which turns the liquid state of the mix gradually to a solid one (Stacey, 2011). The great potential that concrete provides to the construction industry pushed manufacturers to develop new types of concrete to suit various situations and applications. Developers also try to make concrete more environmentally friendly and durable. The following sections shed light on the latest concrete technologies and developments that can affect the life-cycle-design of concrete.

3.2.1.1 Components of concrete mix

In order to reuse concrete components and elements in new life cycles these elements must have durability and sustainability characteristics more than that of conventional buildings. Understanding of the concrete mix components and additives that lead to the best results that satisfy durability, sustainability and strength is of great importance. This section presents the new developments regarding the concrete mix components.

- **Admixtures**

To improve the performance of concrete or to increase workability chemical admixtures are used. A number of chemical admixtures have been developed to do the following functions:

-Improve the workability without affecting the strength

- Reducing the water content and improve the strength

- Accelerating or delay the setting time

- Removing air bubbles to improve strength and

- Reducing the shrinkage when concrete hardened.

- **Cement alternatives**

Some alternative materials to reduce the embodied energy of concrete have been introduced to combine or replace cement. Cement has a high embodied energy and CO_2 emission due to the need for very intense heat during the production processes (Stacey, 2011, pp. p17-26).

The following are the most used alternatives:

- Pozzolanic rocks

- Ground granulated blast furnace slag (ggbs)

- Fly ash
- Silica fume
- Calcium-sulfoaluminate-based cement
- Geopolymeric cement
- Burnt shale
- Magnesium-oxide-based cement and
- Limestone flour (fine limestone dust)

Cement is the only component that has a relatively high environmental impact, but the emergence of cement alternatives supports the sustainability of concrete and enhances its position in the world of sustainable applications.

3.2.1.2 Types of concrete

A number of concrete mixes have been improved to provide desired characteristics that make concrete stronger, more durable and suitable for various applications. This section shows these types and their features that make them suitable to be used in the production of demountable elements.

- **Ultra-high-strength concrete**

Typically, the strength of concrete that can be achieved by normal mixes is 40 MPa (N/mm²), by using ultra-high strength mix a compressive strength of about 200 MPa for in-situ concrete could be achieved. This type is very useful in producing thin and slim load bearing elements such as columns and slabs. Three types of ultra-high-strength concrete could be distinguished these types share the same principle of minimizing the void spaces between cement grains to provide higher strength (Stacey, 2011, pp. p.23-26).

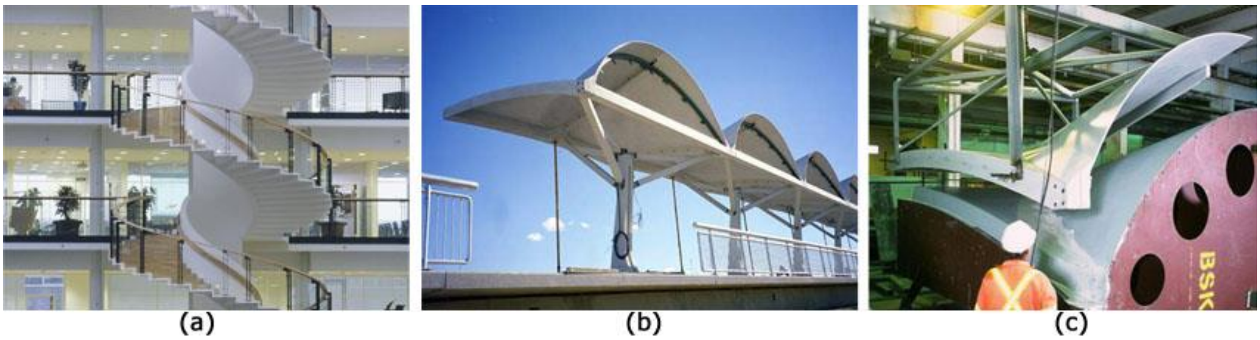


Figure 3-4: (a) Spiral stair made of precast CRC concrete technology elements in Tuborg building, Copenhagen (b), (c) Concrete shells only 2 cm thick made of ultra-high strength concrete at Shawnessy rail station, Calgary(Stacey, 2011)

The design of concrete buildings for disassembly requires easy handling of components during assembly and disassembly which gives ultra-high-strength concrete the potential to provide components and elements of suitable sizes and weights (see figure 3-4).

- **Self-compacting concrete**

This type is suitable for complex geometry forms that need an enhanced finish. Superplasticizer and stabilizer are added to the mix to increase the ease and rate of flow. Also, the heavy weight of this type of concrete helps in filling every part of the mold which compensates the need for vibration.

- **Self-healing concrete**

By the use of bacteria as a self-healing agent or encapsulated polymer precursors many promising studies have been made to increase the sustainability and durability of concrete. Such tchnology helps in free healing of micro-cracks that occur in newly build load bearing structures. In this type of concrete a specific type of bacteria is added to the concrete mix through direct incorporation or by carrier compounds. A microbial activity is occurring causing cracks to be filled and healed automatically. (Jonkers, Thijssen, Muyzer, Copuroglu, & Schlangen, 2010), (Feiteira, Gruyaert, & De Belie, 2013).

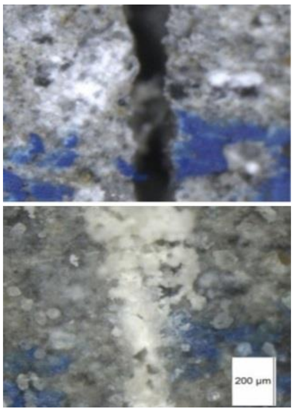


Figure 3-5: Crack filling using self-healing technology (Healcon, 2013)

- **Self-cleaning concrete**

Using particles of titanium dioxide new formulations of cement became pollution neutralizer that converts harmful pollutants into harmless compounds based on photocatalysis process. These photocatalysis processes depend on sunlight to neutralize organic and some inorganic pollutants which keep the concrete surface clean. Such technology leads to decrease the use of harmful chemical compounds that are used to clean concrete surfaces; it also tends to reduce the maintenance costs. (PCA A. , 2015).

Figure 3-6: Use of Self-cleaning concrete in Church of the year 2000 in Rome (Bennett & Graebner, 2015)

- **Light transmitting concrete:**

Using light transmitting cement-based material which consisted of a composite material of optical fiber and cement-based material, a new type of concrete that have light transmitting properties could be developed. In this type optical fibers embedded into a matrix material in a specific pattern and arrangement to become able to transmit light between the two sides of the element (see figure 3-7). Various effects and colors could be obtained when the element is exposed to light which makes it a very suitable material for the decoration of partitions and walls (Li, Li, Wan, & Xu, 2015).

Figure 3-7: Components made of light transmitting concrete. Source (Li et al., 2015)

It could be concluded that the continuous innovation and improvement in the concrete technology supports the life cycle design of concrete buildings. It also helps in providing concrete components and elements that supports the ability for reconfiguration, maintenance, replacement and reuse.

3.2.2 Advantages of concrete with respect to alternative materials

Concrete buildings and concrete as a building material have been ignored regarding reversability and demountability due to several reasons. However, there are strong reasons that encourage considering elements and components made of concrete for circular cycles such as:

- Most of the challenging issues for cyclic concrete buildings and elements either has already a solution or could be solved by the developed concrete technologies such as reusability issues, environmental impact compared to other building materials and deterioration issues.
- The concrete is distinguished by superior characteristics compared to other building materials such as fire resistant, durability and strength, ease of shaping, a variety of types and architectural applications, efficiency and cost effectiveness, safety regarding volatile organic compounds emissions and suitability for indoor air quality. It can provide life-cycle saving more than 20% of total construction cost due to its thermal mass (Concrete Sask, 2016).
- Considering concrete elements for disassembly and reuse will increase its value through easy assembly and disassembly as well as multiple reuses where building materials become more expensive with time (ICAEN, 2004).

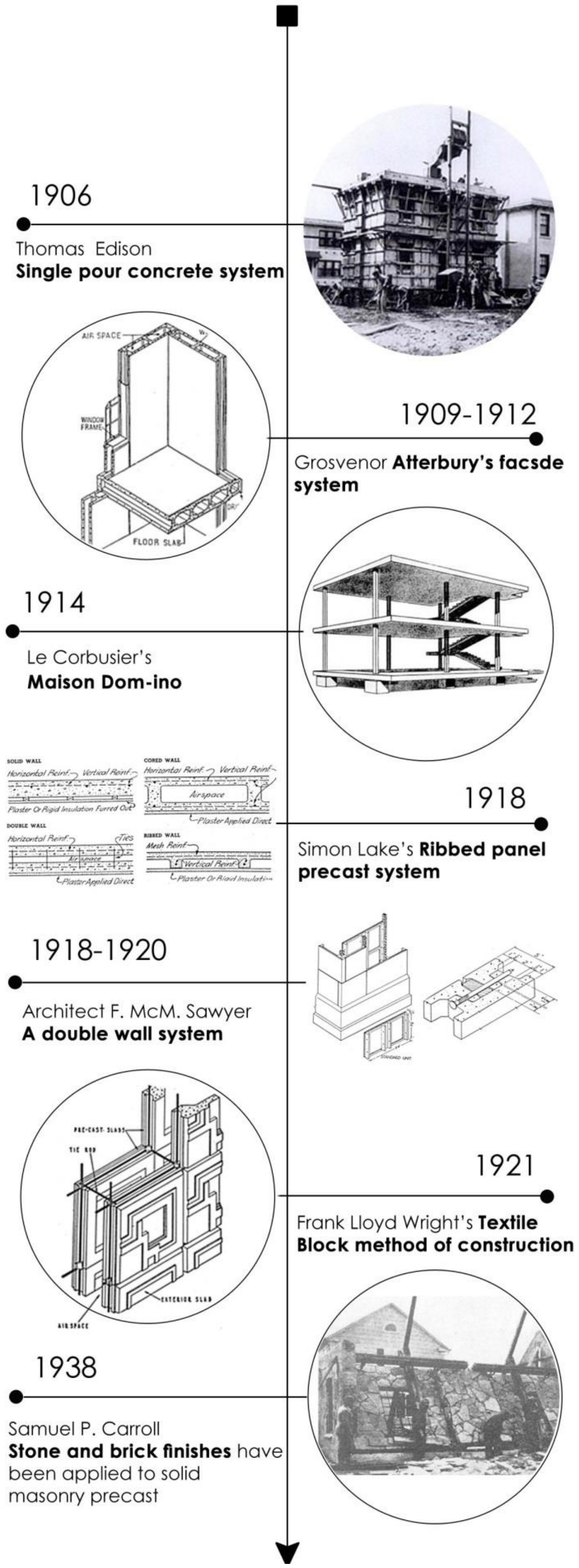
3.2.3 Concrete prefabrication

Prefabricated concrete is mainly characterized by its quality and environmental benefits. These characteristics could be attributed to the controlled environment inside factories and the absence of material waste compared to cast-in-situ concrete. The advantages of prefabrication of concrete include: excellent control of quality, precision molds and closes control of tolerances, diversity of finishes potential for edge detailing, potential for services integration, pre-tensioning and large component for rapid installation.

Prefabricated elements exist in large and small scales. This section provides a brief history of the prefabricated systems and shows their development. It presents the most used technologies and elements and their characteristics and it also discusses their suitability to be designed for disassembly.

3.2.4 Brief history of prefabricated systems

Prefabrication has been used for buildings since the emergence of human civilizations. The Roman for example used prefabricated elements for their buildings and temples. Such prefabrication can be found in many parts around the world. The care about prefabrication has grown up after the industrial revolution due to the emergence of new materials and technologies. At the beginning of 1860 French inventors started to develop systems of concrete panels. In 1906 Thomas Alva Edison came up with a new development in prefabrication: the “single pour concrete system” which was inspired by the casting principles of iron facades. In the 1920’s many projects were built as in Ernst May’s housing project in Frankfurt and in the Tennessee Valley Authority where more than ten thousand prefabricate housing’s units were built. In 1940’s Le Corbusier, Walter Gropius and Konrad Wachsmann were from the first whom showed interest in prefapricated systems through their writings and work (Bergdoll & Christensen, 2008, pp. p.9-12), (Herbert, 1984) (see Appendix 9). The revision of prefabrication before modernism has shown major interest in lightweight components and elements such as timber, brick and steel.



By the mid-1950s some architectural schools such as Soviet Academy of Architecture change its attitude and considered architecture to be practiced as technical rather than artistic craft and declared that prefabricated concrete is the right choice: "*Architects into the factories*" (Bergdoll & Christensen, 2008, pp. p.12-17). Between 1961-65 the Marburger building system introduced in Germany as one of the earliest German construction systems that creates an open fully flexible and variable system that support extension and modification. The system was introduced originally as a diploma thesis for university buildings by Helmut Spieker. In the 1960s Moshe Safdie designed the Habitat 67 housing project in Montreal using a heavy modular concrete system (Bergdoll & Christensen, 2008, pp. p.17-24). In 1989 by the fall of Berlin wall the entrenched panel construction system or "*Plattenbau*" in the former Soviet bloc and the former Soviet republic had become the distinctive style of East Germany and used extensively in West Germany also. In Yugoslavia another prefabricated system "Jugomont System" was developed; this system consisted of large-scale hybrid concrete elements as structural walls and lighter façade systems of metal. Between 1955 and 1991 Angelo Mangiarotti developed a number of prefabricated concrete systems. His work was distinguished by the creativity of dividing the load bearing structure into elements that are easy to be prefabricated economically. His talent in turning junctions and connections into beautiful architectural details gives his designs a striking appearance that shows how building elements such as roofs, facades, windows and services could be combined in a whole expressive tectonic entity (see figure 3-8).

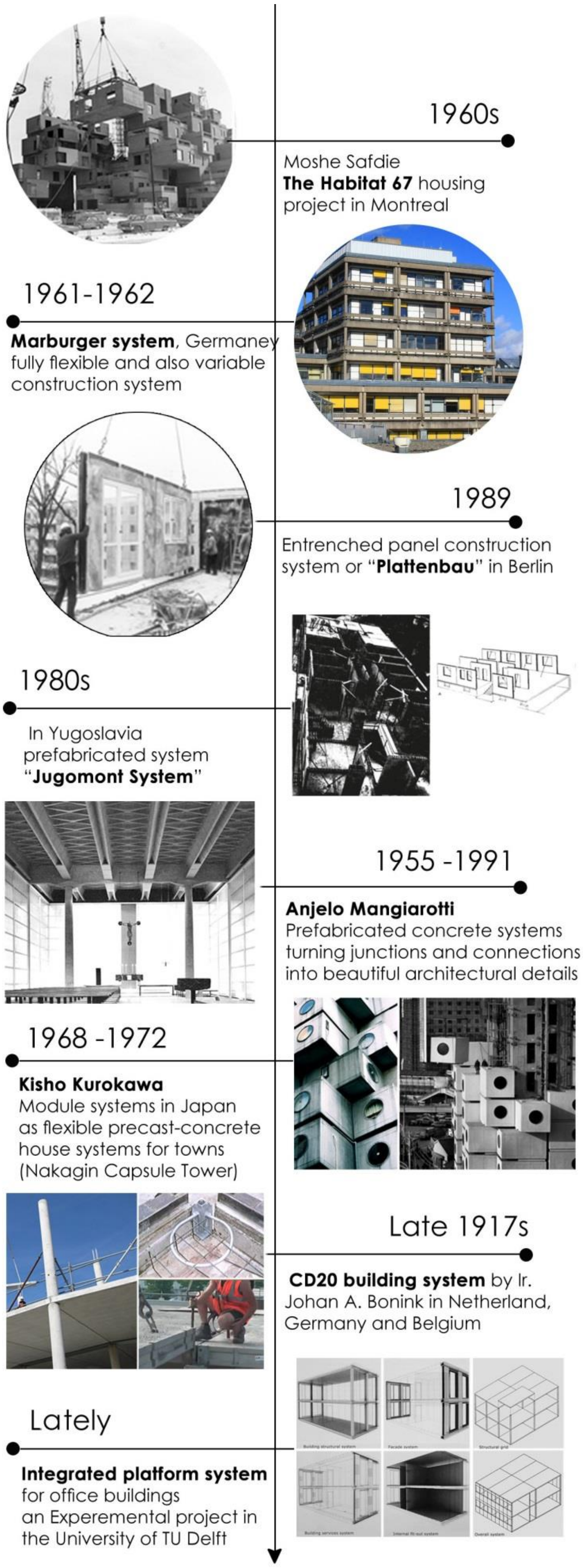


Figure 3-8: Distinctive patents in the history of prefabrication

Mangiarotti works of dividing the structure into load bearing elements and roof spanning slabs that are easy to be assembled with minimum need for steel connections considered a rich material. Such techniques could help in understanding the strategy of designing concrete buildings for disassembly. In Japan module systems were developed by Kisho Kurokawa including toilet capsules for Expo 70 and building systems of industrialized units. These systems were developed for export as flexible precast-concrete house systems to be used in towns. Between 1968 and 1972 Kurokawa used these ideas again in his design of Nakagin Capsule Tower which contains two reinforced concrete towers that accommodate 140 prefabricated units each of one room (Bergdoll & Christensen, 2008).

It can be noticed that the intention of the use of prefabricated systems in general and precast concrete systems particularly was the need for rapid construction in most cases and as a trend in some others. Only one system, the "Plattenbau" that some of its components was disassembled for reuse, despite the fact that it was not developed for disassembly. In this system that was common in East Germany the facade panels were reused successfully in other projects.

3.2.5 Common prefabricated elements and systems

This section presents the common used concrete systems and elements, shows their applications in buildings and construction and indicates their potential for disassembly.

3.2.5.1 Concrete Masonry Units (CMU)

CMU considered the first application of offsite fabrication of concrete (Anderson & Anderson, 2007, p. p.83). CMU exists in many forms and sizes as well as finishing and used to build walls, fences and other applications by grouting these units together usually by mortar (Stott, 2015). The use of mortar causes rigid and closed system that is difficult to be disassembled.

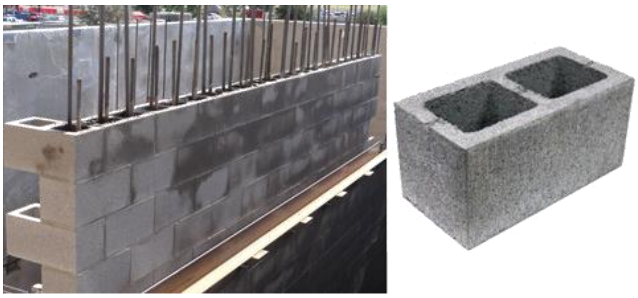


Figure 3-9: To the left a wall made of concrete masonry units, (CMU) (Fresno, 2015)

A fascinating experiment made by Rizal Muslimin aimed to create dry and demountable connections to stack bricks as in figure 3-10.

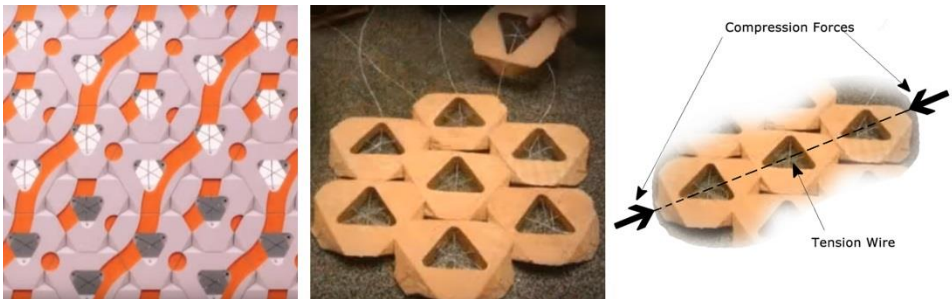


Figure 3-10: Bead Brick in the form of a wall (Muslimin, 2013)

Muslimin used a lightweight brick and connected it to a system of simple intercorrelation using wires that hold the bricks together. That was possible by applying a compression force as in the post tension technology (Muslimin, 2013). Another demountable brick system called Block ARMO has been developed by Armed Omega in late 2015. This system was pronounced by the Mexican Council for Science and Technology as an attempt to provide new construction systems to further contribute to the Mexican society by meeting the demand for decent housing as Juan Reyes indicates (see figure 3-11).

Figure 3-11: ARMO block system (Cázares, 2016)

Despite that this system has positive aspects such as fast assembly and no need for mortar to bind the blocks, mortar is still casted in the circular holes to guarantee the stability of walls. Furthermore, the interlocking relations between the blocks complicate both the assembly and disassembly processes.

3.2.5.2 Autoclaved Aerated Concrete (AAC):

Also called "Foamed" concrete, this type of prefabricated concrete made by adding aluminum powder that makes the admixture expand, then cured in a pressurized steam chamber. This 80% less dense concrete compared to conventional makes the components lighter, more resistant to thermal and sound transitions and easier to be cut and drilled. Such elements used for low-rise structural or non-load bearing applications (Anderson & Anderson, 2007).

Figure 3-12: The use of (AAC) for the production of precast units (Hanley Wood Media, 2015)

These panels usually connected by mortar or adhesives which make the disassembly of these parts challenging and damaging. On the other hand, the lightweight of this type of concrete makes it a preferable type for DfD. Hence new technologies and ways of connection that facilitate disassembly of elements made from this kind of concrete are still needed to be explored.

3.2.5.3 Fiber reinforced concrete FRC

In this type short strands of fibers range from natural unprocessed to high-cost carbon fibers are used. These natural fibers could be made from coconut coir, sisal, sugarcane bagasse, bamboo and other materials (ACI Committee 544, 2002). Fiberglass, carbon and steel fiber are used to replace the reinforcement steel bars inside the concrete. Some positive aspects could be obtained by this technology such as lightness and smaller section panels. It also reduces the need for intensive labor work on steel reinforcement (Anderson & Anderson, 2007). FRC has an excellent flexural-tensile, impact resistance, frost and permeability resistant as well as good resistance to cracking (Rai & Joshi, 2014).

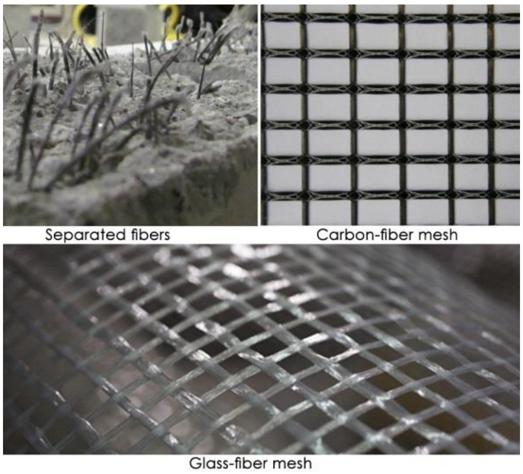


Figure 3-13: FRC (Smart engineering , 2015)

3.2.5.4 Composite panel structure

Also called sandwich panel, this item is made using two sheets of thin reinforced concrete with insulation material usually polystyrene in between (Anderson & Anderson, 2007, pp. p.84-85). Composite panels are usually used in external walls due to its high insulation properties and resistance to impacts.

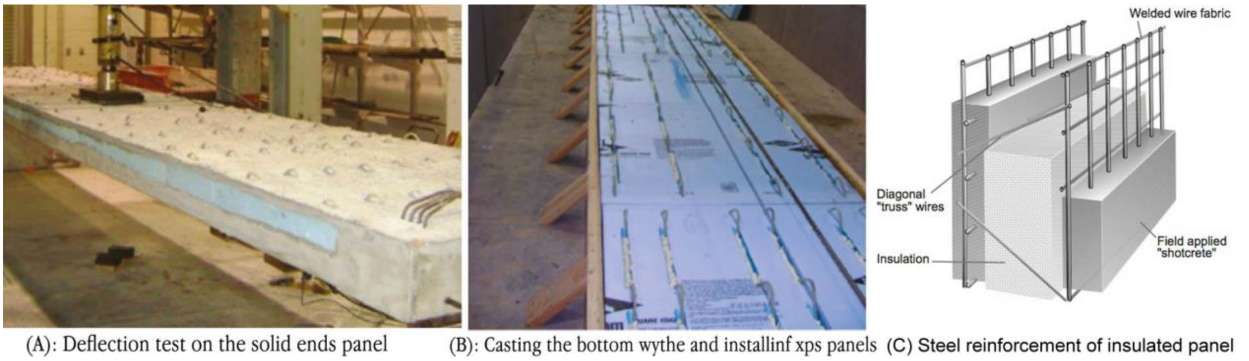


Figure 3-14: Composite panel structure (Kim & You, 2015)

The lightweight of the composite panels and the excellent insulation properties make them a good option for demountability solutions. However, another factor should be considered in this case which is the disassembly of this element to its material levels which provide the ability to upgrade insulation material type or thickness.

3.2.5.5 Rastra system (developed in Austria)

This lightweight hollow panel system is consisted of autoclaved aerated concrete with encapsulated polystyrene for high insulation performance. The panel size is (38×305) of different width depending on the structural and insulation requirements. Its lightweight allows just two workers to handle them. These panels can be arranged vertically or horizontally, allowing the steel reinforcement to be placed in both directions then the core is filled with concrete (Anderson & Anderson, 2007, pp. p.83-85). This system has a fixed system characteristic due to the filling of the core with concrete which complicates their disassembly (see figure 3-15).

Figure 3-15: Rastra construction system (Oak Ridge National Library, 2004)

3.3 Precast concrete production

The production process of precast elements passes through a number of stages from the process of mixing the concrete components to loading of elements to the transporting vehicle. The following sections show the main stages and their distinctive aspects.

3.3.1 The manufacturing processes

Precast concrete is usually casted at the factory in a casting table or pre-prepared reusable mold made of steel, timber, GRP and even concerte. Concrete mixes that allow relatively smooth finishes are used for the production of precast elements which can be controlled through the size of aggregates. The process of manufacturing is started by the design of the precast elements. Then the cad drawing is sent to the mold shop where the mold is designed to have the suitable strength to resist deflection caused by casting process. In general vibrating steel tables are used as a base to most molds types where timber is used to form the sides of the mold and clamped with jacks. It is possible to move the timber sides to alter the size of the casting mold. After the mold is ready it is fitted with the designed steel reinforcement. This stage also includes positioning of the threaded lifting and fixing sockets. The mix then is poured and vibrated to full compaction of concrete. The elements then are stayed at the mold till the concrete developed sufficient strength for handling (see appendix 10) (Dawson, 2003).

3.3.2 Mold use

Tilted steel vibrating table are used in some factories as a part of the mold strategy. In general, these tables are suitable for casting flat panels. When the panel cures the table is rotated to vertical orientation to simplify the handling and transport of the panel. Steel molds in general costs about three times than that of a timber mold but it can cast more units. To achieve a similar cost payment at least 90 units should be casted in the mold. As a role in manufacturing repetition is a key to economy 30 identical casts using a timber mold would give an optimum unit cost (Dawson, 2003).

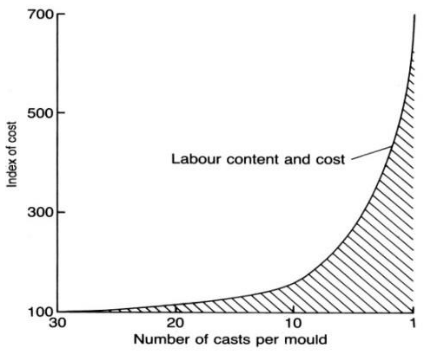


Figure 3-16: The effect of repletion of casting on cost for a typical unit in a timber mold

3.3.2.1 Elements design and mold forming considerations

The forming of mold for special elements design should take into account in addition to the ruse of mold the ease of removal of the precast elements. It can be noticed that the economy of production could be obtained when panels can be separated from the mold without the need to disassemble the mold. This can be achieved by providing slope on the sides of all openings and edges. In this case a complete envelope mold is used (see figure 3-17). Some elements designs required the mold to be formed in parts with removable sections. These parts should be assembled and disassembled each time the element is made which increase the element cost.

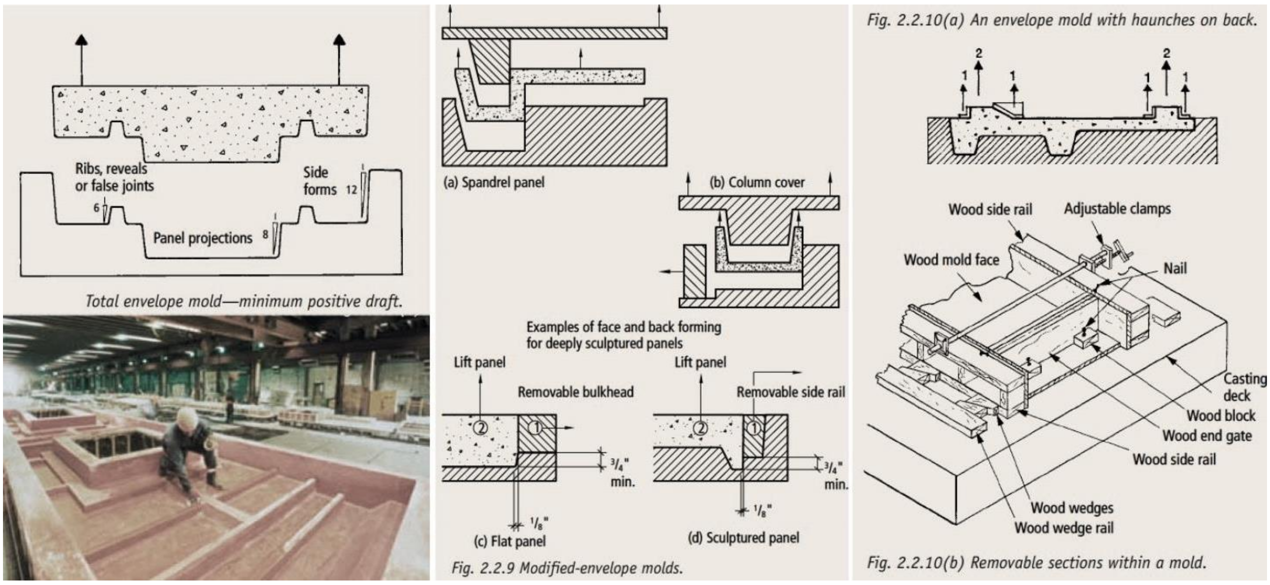


Figure 3-17: Various considerations in mold forming for special elements design

3.3.3 Reinforcement

Reinforcement is vital for precast concrete elements to control the cracks that could occur during the production, handling or installation. It is also important to ensure ductility in case of an unexpected overloading. When stresses that are greater than the allowable concrete tensile strength are expected conventional or prestressed reinforcement is required. Welded wire reinforcement, bar mats, deformed steel bars and prestressing and post-tensioning technologies could be used for precast elements. Secondary reinforcement could include fiber carbon grid coated with epoxy. In case the precast element has a complex shape, non-prestressed reinforcement is normally tied welded together into cages. The size of the reinforcement is governed by the size and dimensions of the precast element and the required cover over the steel (PCI P. , 2007). In addition to the previously mentioned reinforcing technique textile reinforcement using wide variety of materials are possible these days. This technology allows for thinner and lighter precast elements. Textile technology has been used for example in the facades of the Technical University of Dresden and the facades of train station in Arnheim (Fraas, 2013).

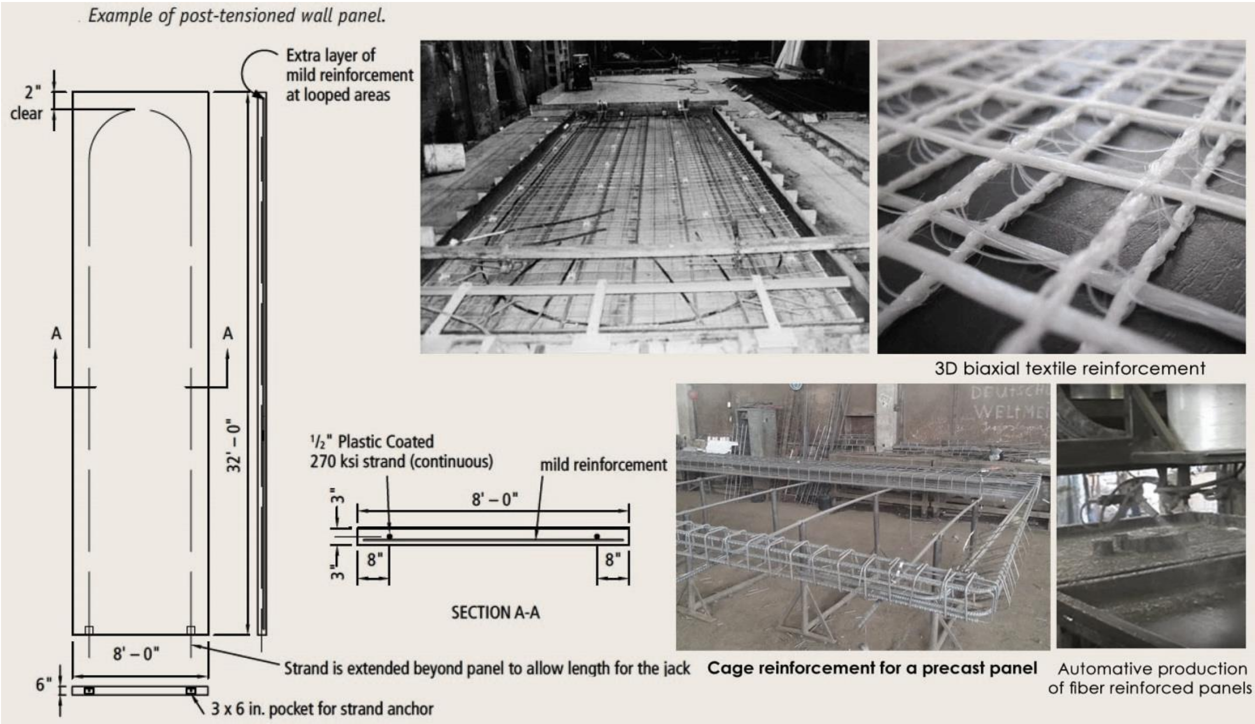


Figure 3-18: Various types of reinforcement technologies for precast elements

3.3.4 Storage

After the precast element gains the required strength it will be moved using a mobile crane to an outer yard in which the elements are sorted and stored. The storage process of precast elements is an important stage which affects the previous and following stages. The storage of precast elements should consider adequate dunnage and bracing. The elements should be kept away from contact with soil to prevent staining, cracking, distortion and warping. Identification marks are added to the elements in a clear place in their storage position to facilitate loading to the transporting trucks.

3.4 Installation of precast concrete elements and components

Precast concrete is usually used in large and small sizes and for various applications from highway bridges to residential building components such as wall panels and floor panels. It is also used for structural and finishes purposes (Anderson & Anderson, 2007).

3.4.1 Transport of precast elements

Components and elements dimensions of precast concrete are determined and limited by the transportation restrictions and the erection weights. Hubert Bachmann and Alfred Steinle believe that these elements must be made as large as possible because subdivisions of these components increase the handling activities during production and assembly. Nevertheless, this could be not the suitable option for demountability which considers the ease of disassembly and reuse of these components in a new life-cycle as a goal and sometimes this may contradict with the very large sizes of components. According to Germany's road traffic Act (StVZO, Straßenverkehrs-Zulassungs-Ordnung) these dimensions are as follows, however, these dimensions could differ from one country to another (see figure 3-19) (Bachmann & Steinle, 2011), (Dawson, 2003).

Table 3-1: Maximum dimensions and weights for road transportation

	without special permit	with annual permit (StVZO cl. 29)
Width	2.55 m	3.00 m
Height	4.00 m	4.00 m
Length	15.50 m	24.00 m
Total weight	40 t	48 t (Tractor unit with self-steering trailer)

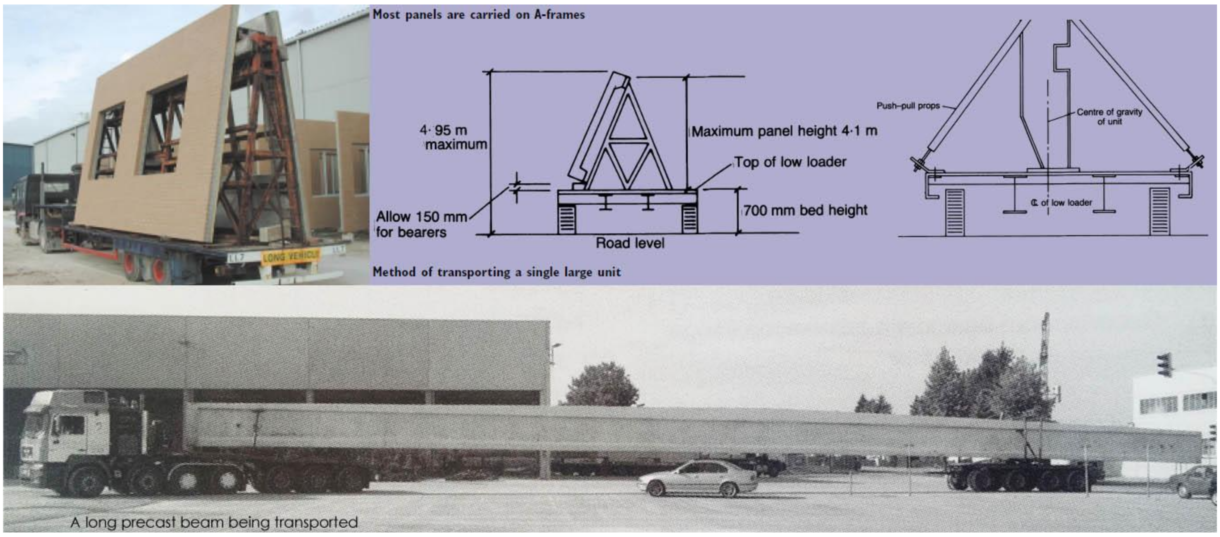


Figure 3-19: Methods of precast element transportation,

Panels are usually carried on a steel A-shaped frame which allows safety and stability during the transportation process. In most cases an extendable trailer can accommodate length up to 18 meters.

3.4.2 Mounting and installation

Weights of components are also restricted to erection machines. While some tower cranes these days can handle up to 30 ton at a radius of 40 meter some mobile cranes can handle about 400 ton. Also there are high load capacity cranes such as crawler –mounted cranes with lifting capacity of up to 1300 ton. Setup of these cranes varies in the time needed depending on their size, lifting capacity and type. Some small mobile cranes also can be used indoor for installation of interior components that cannot be handled by man power. The load capacity of these cranes varies and could reach 3.5 ton (see appendix 11).

3.4.2.1 Methods of mounting and installation

Quality and efficient installation of precast elements requires proper planning and preparation of various aspects that affect the installation process. These aspects include: assembly sequence and methods of erection, providing temporary supports, precaution for final jointing and connections, installation tolerances and handling as well as supply requirements. In general, these preparatory works should be considered:

1. Site accessibility for delivery
2. Provision of quality and panel identification
3. Adequate crane capacity and working clearance
4. Locations and states of lifting inserts (see Figure 3-21)
5. Accessibility for unloading and storage places
6. Suitability of storage area
7. Suitability for storage and erection principle "first in-first out"

Figure 3-20: preparatory works for precast elements installation

- **Installation of vertical elements**

When precast façade panels or other precast vertical elements such as columns and walls are installed the method and work sequence that are usually used is consisted of four main steps. These steps are as follows:

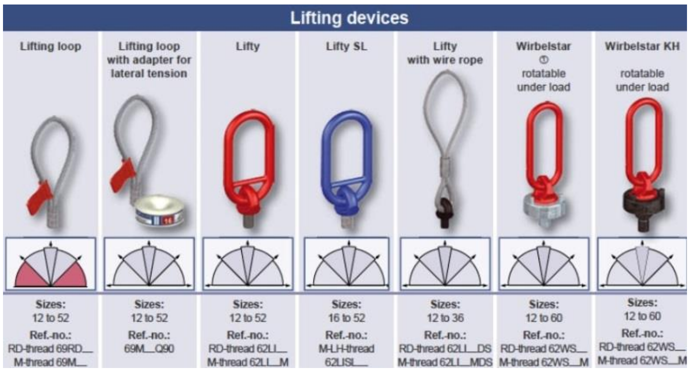


Figure 3-21: Anchorage attachments (Philipp Group)

1. Setting out: This step includes three main operations starting by setting of the reference line and offset line for position identification of the precast element, then, providing leveling shim plates, for exterior walls or columns a compressible form or backer rods on the outer edge of the wall are set.
2. Lifting and installation: This step includes two main operations, lifting and erection of the precast panel to its location using wire ropes and then adjusting the panel to its position and ensures suitable diagonal supports.
3. Grouting: Grouting the work includes three main steps starting by using non-shrink mortar to seal the gaps, when corrugated pipe sleeve connections are used not-shrinkage grout is applied, maintaining the installed panels undisturbed for 24 hours is essential for their stability and fixation.
4. Joint casting and sealing: Six steps are included in this operation, when cast-in-situ joints are used the work starts by installing the rebars at the joints. Then sitting up the forms required for these joints, followed by removing the forms after a suitable period. After that approved sealant and grouting from the outer side of the cast-in-situ joints is applied.

- **Installation of horizontal elements**

Horizontal elements include mainly slabs and beams, the sequence and way of installation of these elements include three main steps as follows:

1. Setting out: The same step that has been used for vertical elements is applied for horizontal elements.
2. Lifting and installation: This step requires preparation of temporary support for slabs and beams, lift and erect the elements to their locations with wire ropes, alignment and leveling of the elements to suit the required setting before placement to the final location.
3. Casting of joints: This step includes four operations, when cast-in-situ joints are used placement and lapping of rebars is the first step. Then setting up the formwork, casting concrete and finally removing forms after the concrete cured and get the required strength (see appendix 12 for more details) (Building and construction authortiy, 2017).

3.5 Environmental aspects

The buildings could obtain more value if their elements and materials lived in loops. The need for such cyclic loops comes from the fact that the consumption of materials and resources will be decreased by disassembly and reuse or recovery. In this case waste is going to be avoided and resources and energy will be preserved. This could be achieved through the cradle-to-cradle design of buildings and the concept of DfD. With regard to concrete buildings some attempts to reuse precast concrete elements showed to be successful despite some challenges and hindrances. Making concrete elements and materials reusable requires considering durability, demount-ability and access issues from early stages of the design and construction process. In this case the end-of-life scenario of buildings will include disassembly and reuse instead of demolition.

3.5.1 Materials flow and waste generated

The process of building and constructing has accompanied through history with massive consumption of materials and resources. Estimates made by the geological survey showed that the building construction consumes about 60% of raw materials used in U.S.(Wagner, 2002). It also produces about 40% of solid waste in the industrialized countries (Feraudy, Comstock, Halcomb, & Hartke, 2012).

3.5.1.1 Cradle-to- grave model of lifecycle of building materials and concrete

Philip Crowther described the current linear model - which also referred to as “Cradle-to-grave” model of the life-cycle of building materials. He indicated that materials pass through a number of stages from extracting to demolition and accompanied with potential environmental impacts at each stage. He showed that pollution and waste production considered the key features of this model. Where the majority of the materials are dumped in a landfill at the end of buildings life (Crowther, 1999). The building industry consumes around three billion tons of raw materials which are 40% of total raw materials consumed by human societies (Lessen & Roodman, 1995). In Europe only, more than 970 million tons of waste per year (and increasing) are generated by building industry according to European commotion in 2006 (E.C. Dg Env, 2011). The environmental building news estimated that 25% of buildings existed in 2000 will be replaced by 2030 (Ogbu, 2010).

3.5.1.2 Concrete waste

Concrete which is the most used building material(Crow, 2008) ends up as unnecessary waste in landfill in almost all over the world(Csi, 2009). Tomas Jr believes that the exact quantity of concrete waste generated in the US and many other countries around the world is unknown at the moment (Jr, 2015). Kumar Mehta stated that over 10 billion tons of sand and natural rocks are used for concrete manufacturing around the world every year. Also over 11 billion tons of construction and demolition waste are generated (Mehta 2002 p.23-24), 50% of which are concrete wastes (Tam, 2008).

3.5.1.3 Embodied energy of building material and elements (life-cycle assessment)

Besides the two initial problems of waste production and pollution the embodied energy - also called life-cycle assessment - of building materials can range from 30-50% of total life-cycle energy(2) of a building (Durmisevic, 2010, p. p.26). However, this amount could reach 400% in the near future due to the decrease of running costs. This decrease is attributed to the use of energy efficient appliances and effective insulation materials as well as solar energy systems as Luisa F. Cebeza believes (Cabeza et al. 2013 p.537). The embodied energy and CO_2 emissions of concrete are relatively high due to the use of Clinker in its components. The production of clinker produces about one ton of CO_2 per ton of clinker (Cabeza et al., 2013). E. Gartner argued that each cubic meter of concrete produced is accompanied by about 0.2 t CO_2 emissions, equivalent to 0.08t CO_2 per ton of concrete. Compared to other materials such as steel these quantities considered low. More than one-ton carbon dioxide emissions is generated by the production of 1 ton of steel (Gartner, 2004). A study by Struble and Godfrey compared the environmental impact of a reinforced concrete beam and a steel I-beam designed for the same engineering function. The study found that the production of the concrete beam required much less energy and had a lower net environmental impact than that of the steel beam (Struble & Godfrey, 2012). Another two studies compared the environmental impact of steel and cast-in-situ concrete buildings. One of these studies is by Guggemos, Asc and Horvath and the other is by Johnson. These studies showed interesting results that lead to the fact that cast-in-situ concrete contribute to higher environmental impact mainly through construction and end-of-life stages. Such environmental impacts can be overcome when precast concrete is used and the reuse of elements is considered (Guggemos, Asce, Horvath, & Asce, 2005), (Johnson, 2006).

[2] -Total Life cycle energy of a building include both Embodied energy and **operational energy** which is the energy needed to maintain the inside environment such as lighting, heating and cooling and operating appliances(Cabeza et al., 2013)

3.5.2 Cradle-to-cradle design and the alternative life-cycle model

An alternative to the linear model of the life-cycle of building materials and components could be derived from cradle-to-cradle design. This alternative is an eco-effective approach that tends to reduce CO_2 as Braungart and McDonough believe. They argue that this approach leads to enhance the quality and productivity of materials through subsequent life cycles (Braungart, McDonough & Bollinger, 2007). Crowther suggests implementing this approach to architecture and building through reuse of building materials and components by replacing the stage of demolition with disassembly (Crowther, 1999) (see figure 3-22).

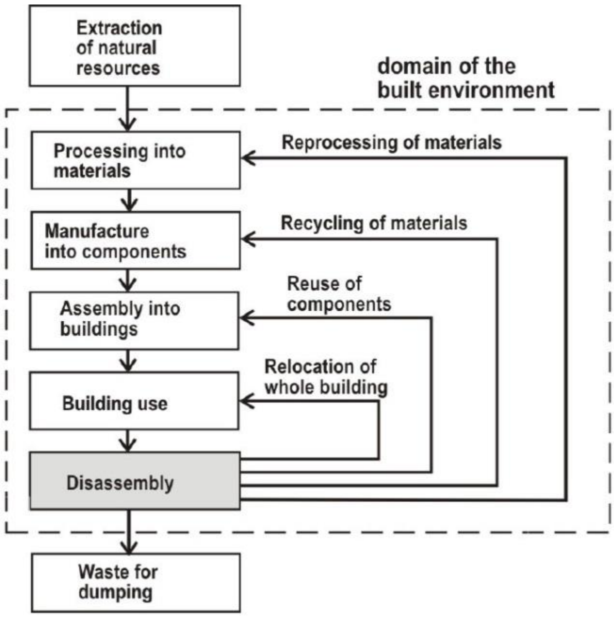


Figure 3-22: An alternative scenario that enables reuse of elements and materials through Disassembly (Crowther 2005)

3.5.2.1 The reality of reuse option

The concept of reuse and recycle is an ancient concept which was the norm throughout the world until the 19th century and being practiced widely in many industrialized countries (Addis, 2006, p. p.9). From earliest masonry construction in ancient Egypt to the use of iron in Roman times 100BC and AD500 the elements were used many times and their recycle was considered (Addis, 2006). Nowadays the construction industry in the industrialized and developed countries is exposed to a growing pressure to increase the reuse and recycling of materials and components. A lot of successful projects constructed from salvaged and reused materials have been accomplished around the world. In Sweden two students' accommodation projects have been made from reclaimed materials, the Udden project and the Nya Udden project in Linköping. In 1997 the Udden project was constructed using materials from two abandoned resedential buildings from the 1960s. These abandoned buildings were scheduled for demolition due to an economic decline in the area. The buildings were made of cast-in-situ reinforced concrete where a diamond saw was used to cut the reinforced concrete into manageable pieces. Wall elements, floor elements, foundations, clay brickwork, insulation materials and other items and components have been reused in this project. In 2001 the Nya Udden project was constructed using materials from precast concrete buildings dated to 1970s. Over 400 pre-cast concrete elements were used. Partition walls, outer wall elements concrete beams, concrete staircases and other elements and components have been reused also in this project. Both of the two projects have suffered from a higher 10-15% costs compared to similar buildings made of conventional techniques and materials due to non-conventional processes and lack of experience (Addis, 2006).

While the previous projects were not cost-effective other experiments represent more successful cases such as Kummatti housing estate rehabilitation project in Raahe, Finland. During 2008-2010 even a small-scale reuse occurred, but it was successful and resulted in 36% savings in construction costs (Huuhka, Kaasalainen, Hakanen, & Lahdensivu, 2015)

Figure 3-23: Kummatti housing estate in Raahe, Finland; part of the buildings was disassembled, and concrete panels have been reused for carports (Huuhka et al. 2015)

Another successful project in which a bigger scale of reusing precast concrete panel occurred is the design of new housing in Mehrow near Berlin by Herve Biele. The project included reuse of precast components from an unwanted 11- story slab block "Plattenbau" for the construction of new houses. In this project 30% less cost has been achieved (see figure 3-24) (Stacey, 2011).

Figure 3-24: Reuse of precast concrete slabs and panels for new housing construction in Mehrow near Berlin (Stacey, 2011)

Another example of reusing concrete elements was by the federal ministry of transport, building and housing in Germany in 2001. This project was a part of a research project "Recycling prefabricated building component for future generations" that aims to test the potential of dismantling and designing a house using reclaimed components. The project shows that hand procedures using light machinery were more applicable than heavy-duty ones. The reused building parts are 50% cheaper than new concrete building parts and the total building costs when using reused elements are 26% less than using new ones (Glias, 2013).

3.5.2.2 End-of-life scenarios of buildings

Every building has to reach its end-of-life sooner or later despite the many reasons that could lead to listing the building to demolition and can be all related to obsolescence(3) as Crowther believes (Crowther,

[3] - "**Locational** obsolescence: the building's function is no longer appropriate or needed in its current location.
Functional obsolescence: the building's function is no longer needed within society.
Technical obsolescence: the building can no longer attain expected performance standards.
Physical obsolescence: the building or its components have fallen below acceptable standards of safety or amenity due to deterioration.
Fashionable obsolescence: the building no longer meets current standards of style and trend."(Crowther, 1999)

1999). The building has two dominant scenarios, either demolition or disassembly. To be more specific some kind of disassembly also occurred in the first scenario where valuable materials and components, as well as services, could be stripped. While the second scenario is preferable due to its environmental benefits the first is still dominant in many if not all countries around the world (Durmisevic, 2010, pp. p.22-24). According to Crowther a loss of as much as 25% of the building's total construction and operational energy is used by the act of demolition. This energy loss could be noticed specifically in buildings with short life spans (Crowther, 1999). Many guidelines and studies in U.S. have been made to address the deconstruction of buildings. These guidelines and studies included the deconstruction techniques and tools, policies and regulations as well as the market issues. Also, the feasibility of deconstruction and recycling of salvaged materials was considered in these studies (Hamidi & Bulbul, 2012).

3.6 Conclusion

At the end of this chapter and the discussion that considered the construction and assembly of concrete buildings the following points can be concluded:

- The life-cycle-design of buildings requires reconsideration of the conventional construction of concrete buildings.
- The concrete buildings that have been built using cast-in-situ construction or cast-in-situ connections are difficult to be disassembled.
- More effort should be dedicated to the end-of-life scenario at the field of concrete technologies.
- Demolition is still the most preferable option when removal of concrete buildings is required.
- Concrete technologies are able to support the development of demountable elements.
- The successful attempts in which some precast buildings have been disassembled for reuse have proven the ability of precast buildings to be disassembled. This success could be noticed despite that many aspects that decide the transformation capacity and disassembly potential of these buildings are still missing.

Chapter 4. Evaluation of the disassembly potential of precast concrete systems

Introduction

Concrete buildings can be constructed either using cast-in-situ or precast. While cast-in-situ construction produces buildings that are monolithic and interpenetrating, precast systems are independent elements and could have higher potential for demountability (Salama, 2017). This study suggests that some common precast concrete systems could be developed to have higher disassembly potential and consequently higher sustainability. To make this applicable this section is going to analyze and evaluate these common precast systems with regard to their disassembly potential. Based on the knowledge model of Durmisevic which considers eight aspects of design for disassembly and through independence and exchangeability as a design criterion these common systems will be evaluated. Durmisevic believes that the decision-making support regarding the disassembly potential of a building configuration can be taken through three main aspects. These aspects are, material levels, technical composition and physical integration. (Durmisevic, 2010). The results of this chapter will help in specifying aspects that need care during the decision-making process when demountability issues in the design of these common precast systems should be considered.

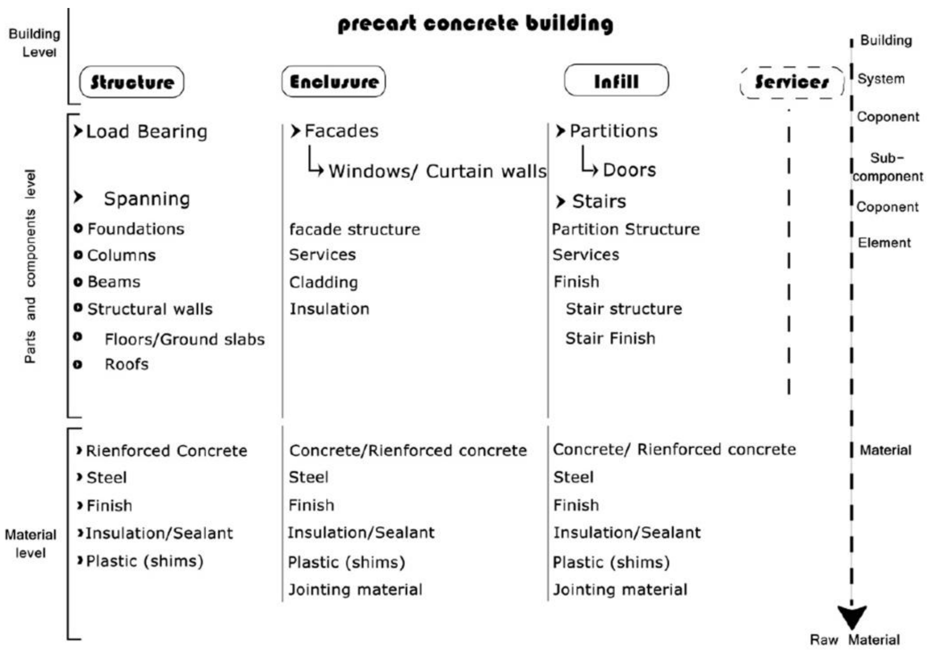
4.1 Analysis and evaluation framework

To simplify their study the concrete buildings can be divided into building functional levels including: structural, enclosure and lnfill systems - as systems that can be made of concrete - in addition to other systems such as services and outlets. Each of these systems have physical system levels which include further divisions of the building functional levels. For example, the structural system has a load bearing level and a spanning elements level. Each of these physical system levels has component and material levels (see figure 4-1). The current precast industry provides elements and components for all the structural, enclosure and infill systems. As it can be noticed from the precast concrete association and other manufacturers such as the American precast/prestressed concrete institute PCI, the Canadian Hy-Grade precast concrete company the British Bison precast manufacturing limited company, and the American National precast concrete association NPCA and many others.

4.2 Analysis and evaluation criteria for demountable precast systems

In 2010 Durmisevic developed a conceptual and knowledge model that takes into consideration eight DfD aspects. These aspects cover three levels of decision making regarding the typology of configuration of any building as discussed in chapter one. Based on these criteria the common precast concrete systems are going to be analyzed and evaluated. Table 4-1 shows a schematic integration of material levels that could be existed in precast concrete buildings. It is clear that precast concrete buildings are mainly made of precast concrete elements and components. These components should accommodate the building services such as the electrical and data systems as well as the water supply and drainage systems. Another aspect that characterizes the precast concrete buildings is the high degree of separation of building functions through individual components and elements. Also the material levels are not fixed into one level which emphasizes that precast concrete buildings have the essentials of the dynamic open configurations.

Table 4-1: Schematic integration of material levels in precast concrete buildings based on Durmisevic conception



4.3 Building levels and the technical composition of precast buildings

As the previous section shows, the emancipation of independent physical levels leads to provide systems with the ability to change and reconfiguration. It also helps in the extension of the life of the physical levels through reuse and replacement. Figure 4-1 shows the functional levels of precast concrete buildings and its hierarchy which include systems and subsystems. These systems shape the physical state of the building and consisted of components and materials. These components and materials are integrated together to provide the functions and appearance of buildings. The technical composition of precast buildings in this diagram will be studied and evaluated based on the previously mentioned conceptual and knowledge model of Durmisevic.

The structural system in precast buildings that provides the building with the required stability and support is mainly made of concrete as a dominant material. The enclosure system is mainly characterized by the building facades which integrate different materials and functions. Concrete as a building material cannot provide the building with all the required functions. The need for an effective thermal insulation and suitable exterior appearance required the façade systems to integrate different materials in its technical composition. The last physical system that could be made of concrete is the infill system which integrates mainly the stairs and partitions.

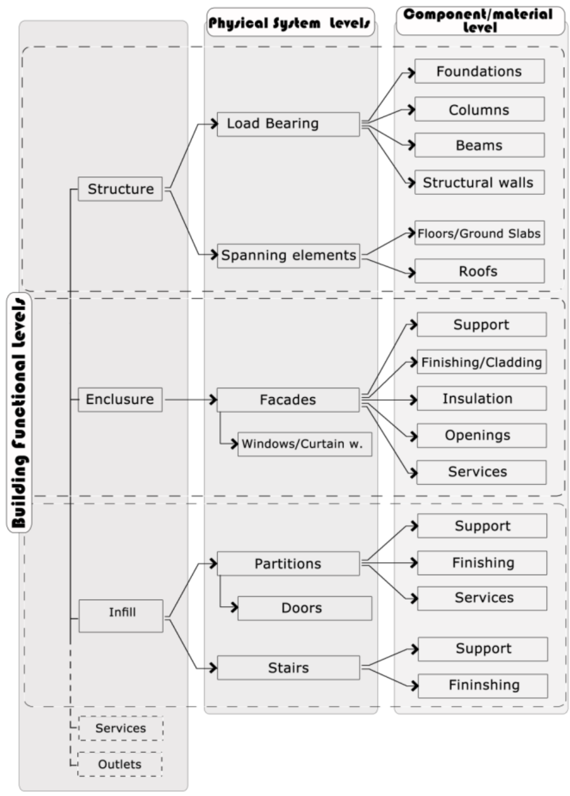


Figure 4-1: The technical composition of concrete buildings

4.4 Suitability of building types for disassembly

The fact that all material levels in the technical composition of a building should be affected by the DfD must be the ideal case that governs the design process for all building types. In concrete buildings the specialty of elements, their sizes and shapes, their reuse potential and the use strategy of buildings affect the suitability of some building types for disassembly. Despite the benefits that could be gained from total DfD of all building types made of concrete there are some factors that should be taken into consideration. That should be the case till design for disassembly become a common practice. These factors are regarding types of buildings and level of disassembly. Durmisevic believes that in addition to the exchangeability the use strategy of the building decides what kinds of buildings should be designed for disassembly. This study suggests that design for disassembly is primarily required for series of projects or buildings that have the same owner. These types of projects are most of the time characterized mainly by repetition and standardization such as schools, hospitals and residential buildings. In this case the disassembled elements can be easily reused for the extension of other buildings or the construction of new ones.

4.5 Levels of disassembly

The level of design for disassembly can be identified using the life-cycle coordination matrix which was developed by Durmisevic. This matrix could be used for concrete buildings by specifying the technical and use life cycles of precast elements for different functional levels as in figure 4-2. However, these values are for conventional buildings, precast elements are supposed to serve a longer time due to the better quality in which they are usually produced. In this case the life-cycle coordination matrix is going to identify the technical life-cycle of the precast elements and their minimum reuse potential for at least full second life-cycle.

Table 4-2: Typical life expectancy of concrete building components and integrated services and finishes, (Stacey, 2011), (True Professionals, Inc., 2014), (AECB)

Building level	System level	Component Level	Expected Life	Average expected Life
Structure	load bearing	Foundation	100-120	110
		Columns	81-100	90.5
		Beams	81-100	90.5
		Structural walls	81-100	90.5
	Spanning elements	Floors/ Slabs	75-78	86.5
		Roofs	100	-
Enclosure	facades	Support	100	-
		Finishing/cladding	100	-
		Insulation	100	-
		Openings	-	-
		Services	7-15	11
Partitions and stairs	Partitions	Support	100	-
		Finishing/cladding	50-100	75
		Services	7-15	11
	Stairs	Support	81-100	90.5
		Finishing/flooring	50-100	75

Table 4-2 shows the typical life expectancy of concrete building components and elements according to Stacy and others. The values in this table will be used in the life-cycle coordination matrix. Due to the continuous development of concrete technologies and the improvements of durability and strength the actual values could be much higher than these in the table. However, these values will be considered as a reference. These values also vary according to the quality of materials and the exterior exposure. The following equation could be used to find the estimated design service life of concrete elements according to D J Kelly (SBSA, 2007).

EDSL-R = RSLC x Ax DF [4]

[4] : Where: EDSL: estimated design service life for regulation
RSLC: reference service life – structural component, not accessible: value 60 years.
The factors should vary by no more than 0.2 from 1.0.
A: quality of materials factor – Portland blast furnace slag cement (to British Standards) with good coverage of reinforcement: value 1.1.
D: External exposure – inner city location away from coast and significant frost, frame covered by cladding: value 1.2
Therefore, EDSL-R = 60 x 1.1 x 1.2 = 79 years

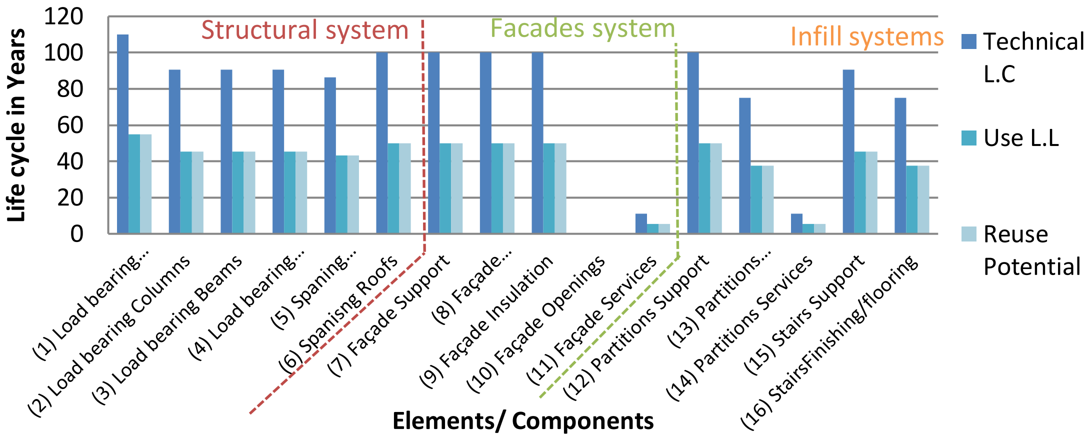


Figure 4-2: Lifecycle coordination matrix of concrete component

Based on the fact that after the second reuse of elements the environmental and economic benefits can be gained as Durmisevic proved (Durmisevic, 2010). Total design for disassembly could be applied to buildings that are designed to serve for a specific time according to a predefined use strategy and within a lifetime less than half of the minimum concrete element lifetime. In this case the potential to reuse all of the building elements and material levels in a full second life cycle is existed. Design for partial disassembly will be more suitable in some building levels such as facades when their elements and components have high exchangeability rate, and when the remaining technical life allows for further reuse.

4.6 The structural level of precast buildings

Three main levels of the precast buildings could be made of concrete: the structural system is the first level. The function of the structural level is to support the building and all the other building levels. Based on the technical composition of the precast buildings showed in figure 4-1 the various levels of the technical composition will be investigated.

4.6.1 Physical system level and component/ material level

This section reviews the most common precast elements of the structural system and their physical system levels and material/component levels. It also provides a brief overview of the obstacles to the disassembly potential of these common elements.

4.6.1.1 Foundations

The heavy weight is one of the challenges to the use of precast foundations. That is why foundations are usually cast-in-site; however, heavy foundations in some cases are made by a combination of precast and cast-in- situ concrete. There are three main types of precast foundations that are commonly used according to (Bachmann & Steinle, 2011) :

1. A complete unit of foundation and column
2. Pocket foundation
3. A foundation with holding down bolts

Figure 4-3 below shows these types. Despite the fact that the first type has been criticized as bulky, it has been used due to dispense for column–foundation connection and simplicity of assembly (Bachmann & Steinle, 2011). Due to the disadvantages of this type in addition to gathering of different functions of the column and the foundation, this type will be eliminated from the evaluation process. The second foundation type is pocket foundation. The primary form of this foundation was a pad footing with a unified pocket on top. This type has been replaced by the true pocket foundation in the body of the footing due to economic reasons.

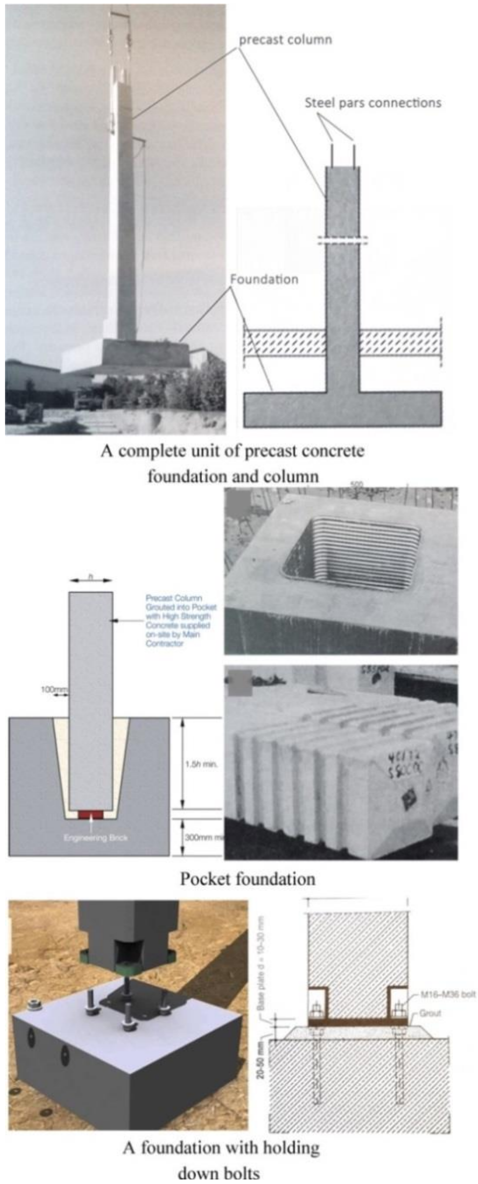


Figure 4-3: The main common types of precast foundation

The column is inserted to the pocket and the load force is transferred to the foundation using skin friction (Irish Precast Concrete Association (IPCA), 2007). This type is accompanied by the use of cast-in-situ concrete to connect the column to the footing which produces a permanent connection that cannot be disassembled. Unless a new demountable connection is developed, this type of foundations considered inappropriate for demountable structures. The last foundation type is the foundation with holding down bolts. This type is usually used with shallow structural depth and moderate column loads. In most cases grout is used to protect the steel bolts and plate (Bachmann & Steinle, 2011), (Irish Precast Concrete Association (IPCA), 2007). This method produces permanent material that not only blocks access to the connection but also makes the disassembly difficult.

4.6.1.2 Columns and beams

Columns and beams transfer the loads of the structure to the footings. Precast columns are manufactured in many cross-section shapes and could be used for one storey buildings and multistory buildings up to five storeys. Cylindrical columns could be produced with high strength concrete using spun technology to have hollow cores. Precast columns usually have concrete corbels to support beams. These corbels could be positioned in two opposite sides, three sides or four sides (Bachmann & Steinle, 2011), (PCI P. , 2015). Fixing devices are used to connect columns with beams. The design of these connections differs from one system to another where the most common types are dowel bars cast in corbels and fixing bolts cast in columns. In the second fixing type steel plates in beam are used (see figure 4-4) (Peikko, 2016).

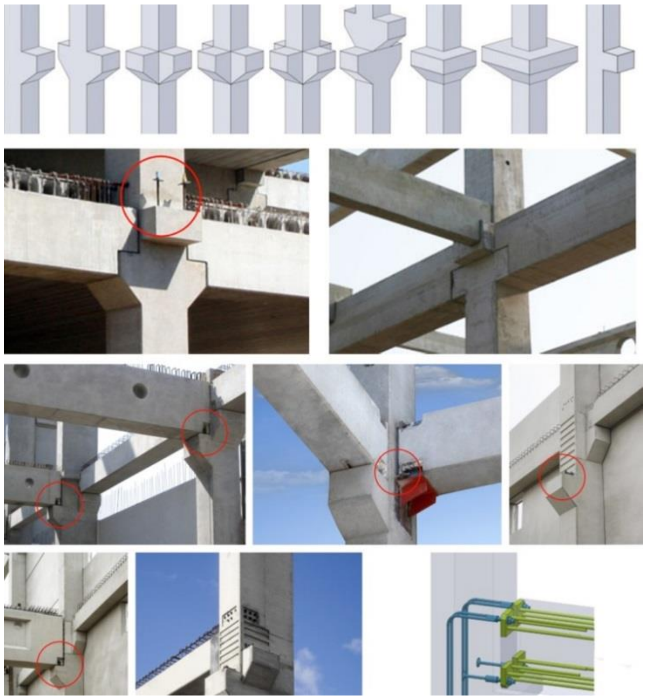


Figure 4-4: Precast columns and their concrete corbel types and beams and their connections.

In addition to the concrete corbels other types are manufactured by a number of precast European companies using steel. The main types of these steel corbels are AEP steel connection bracket by Anstar, and PCs hidden corbels by Peikko company. Each of these systems has a special beam connection design. In this study the analysis and evaluation will be restricted to the conventional concrete corbels.

In some cases for multy story buildings columns are manufactured in parts where column-to-column connections are used. Two main types are used to connect column parts together: bolt connection and release channels (see figure 4-5) (Oberbeton, 2009-2015)

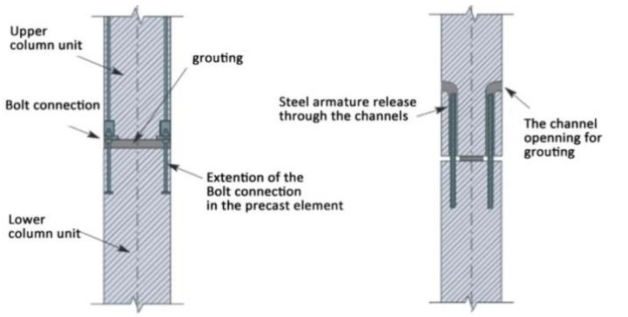


Figure 4-5: The main two column-to-column connection types

4.6.1.3 Structural walls

According to a study by the New Zealand Concrete Society two main types of precast concrete structural walls are existed: monolithic wall system and jointed wall system.

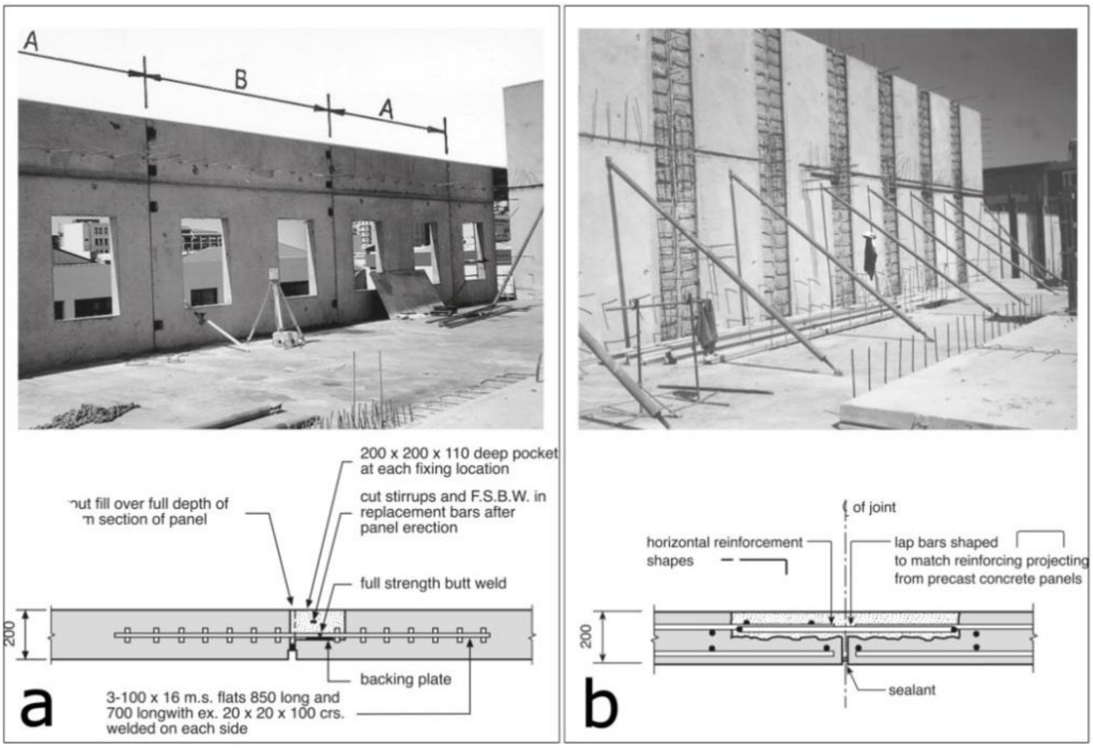


Figure 4-6: Types of structural wall, to the left jointed wall system, to the right monolithic wall system.

In monolithic wall system strong connection are usually used, while in jointed wall system ductility with energy dissipation in the connection is allowed (see figure 4-6) (New Zealand Concrete Society, 1999). Due to the initial aim of the production of these structural walls which is fast assembly, these elements most of the time connected using cast-in-situ concrete. This connection method makes the disassembly of these elements very difficult. However, the development of demountable connections will help in preventing from demolition and add demountability value.

4.6.1.4 Spanning elements

The precast spanning elements that are common and used could be found in various types. The most important factor that decides the form of these elements is the length of its span. The following are the most common types:

1. Hollow core slabs
2. Ripped slabs
3. Composite plank floors

The first two types are used as independent elements. Composite plank floors are part of a composite system. In this system the concrete planks are used to receive a cast-in-situ layer that turn them to a monolithic entity that cannot be separated. For that this type will be eliminated from analysis and evaluation.

- **Hollow core slabs**

This type is preferred due to a number of aspects that make it economical such as its light weight and fully automated production. These slabs could be produced either prestressed or conventional where spans up to 18 m with 40 cm depth can be achieved (Bachmann & Steinle, 2011). In some cases these slabs are accompanied by a cast-in-situ layer to make a monolithic floor. Such layer helps also in resisting point loads and connecting these slabs with the structural elements (New Zealand Concrete Society, 1999) (Allen & Iano, 2009). Despite the fact that the use of cast-in-situ concrete with these slabs is common but this system can also work without cast-in-situ connections. When the design of these slabs takes into consideration loads requirements cast-in-situ connections can be eliminated (see figure 4-7).

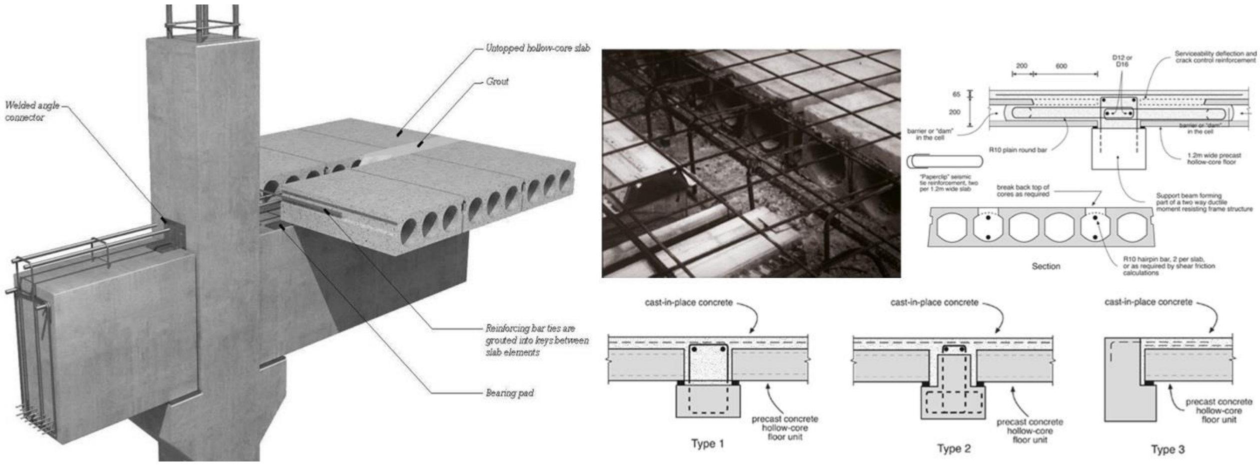


Figure 4-7: Hollow core slabs and their connection methods.

- **Ripped slabs**

Ripped slabs are used for long spans or high loads. These slabs are also produced either conventionally reinforced or prestressed. Two main types are common: double-T and single-T. Double-T units can be produced up to 16 m length, 70-80 mm depth and 3 m width, the ribs for these dimensions are usually 1.2m (Bachmann & Steinle, 2011). These slabs are used for floor and roof components for various structure types. It could be produced either pre-topped using flange thickness of 10.16 cm or field topped with 5.08 flange where a layer of cast-in-situ concrete of 5-10 cm thick is added (PCI P. , 2015). Figure 4-8 shows the use of precast double-T slabs and the method of connection. Some slabs are manufactured with thin-flange where a total cast-in-situ concrete topping is added. The other type is with thick flange where the cast-in-situ topping is added at joints (Concrete Technology Corporation, 2013). Here it is important to mention that the use of cast-in-situ concrete to make connections and jointing the ripped slaps shapes a hindrance to the demountability of these elements.

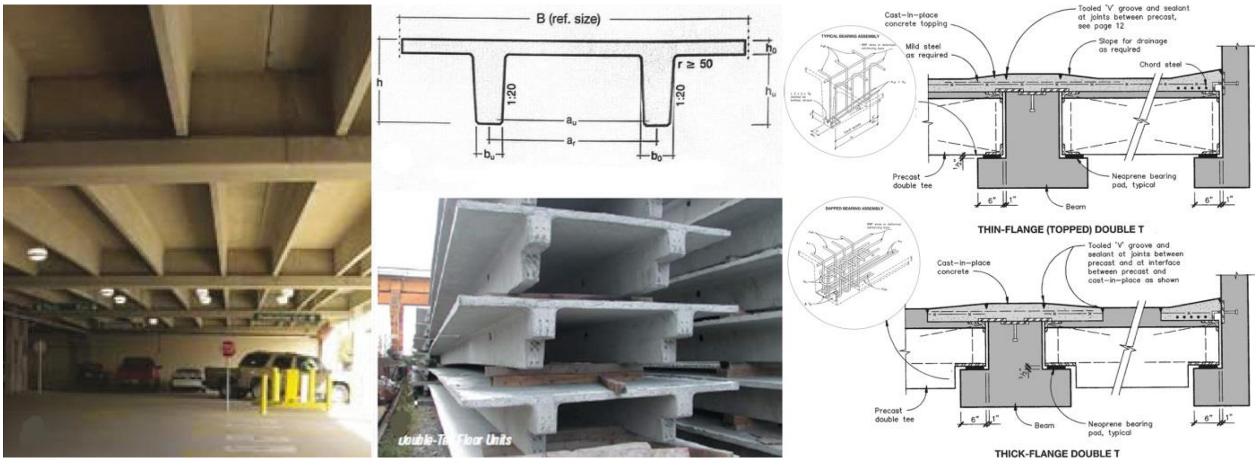


Figure 4-8: Ripped slabs and their connection methods

4.6.2 Analysis of the disassembly potential of the structural system

Due to the long technical life of concrete elements in general and the structural elements particularly this study recommends to design the structural system for disassembly. Designing these elements for disassembly will allow reuse and reconfiguration. The structural system does a unique function by transferring loads and supporting the whole building. This makes the relation between this system and the other functional systems of the building critical. That’s why not only the connection types is what decide the disassembly potential of this system but also the assembly aspects. Based on the previous mentioned aspects of the typology of configuration analysis of this system will be performed. Taking into consideration that reinforced concrete will be treated as a unified material regarding its material levels when considering independence and exchangeability. And the down cycling process - which include crashing the concrete and separating the reinforcement steel – will be the last option when the elements are totally exhausted.

4.6.2.1 Material levels

The independence and exchangeability of material levels in the structural system is achieved due to its unique function which is supporting and loadbearing. However, when some kind of finishes is going to be applied to the structural elements the independence and exchangeability of material levels should be considered.

4.6.2.2 Technical composition

The independence and exchangeability of the technical composition of the structural system is decided by the hierarchal arrangements of materials and the relation between materials. For the structural system the gravity not only decides the hierarchal arrangements of the elements but also the relation between them. It can be concluded that gravity dominates the arrangements and relations between elements and impedes its independence and exchangeability (see figure 4-9).

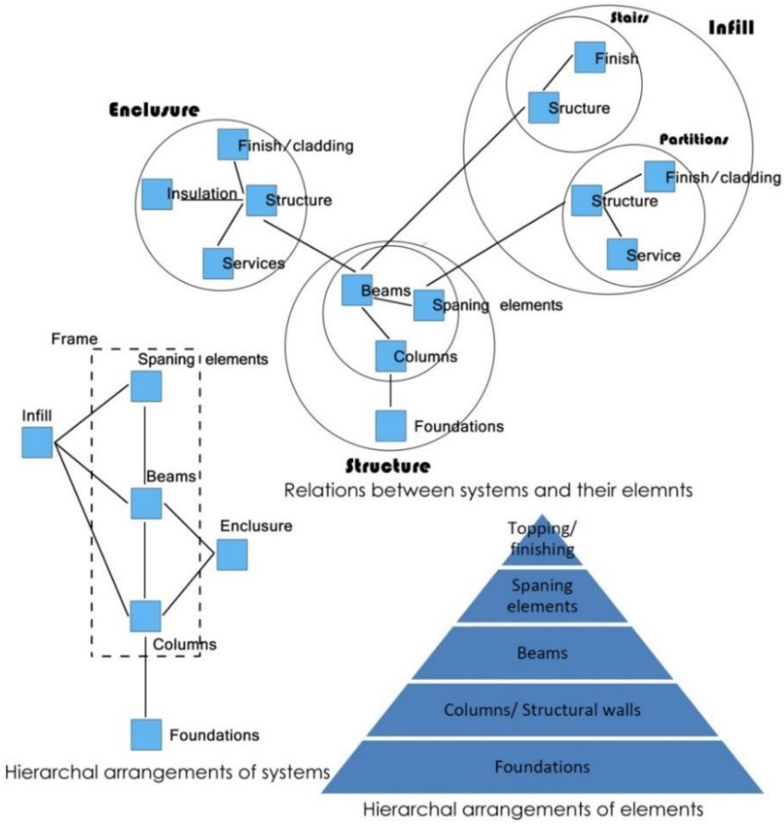


Figure 4-9: Technical composition aspects of building system and their elements

4.6.2.3 Physical integration

The independence and exchangeability of the physical integration of the system and its elements is determined by: the type of connection, the geometry of element edge and the assembly sequence. It is clear that from one structural system to another the type of connection and the geometry of element edge might differ. Despite the previous fact, the assembly sequence most of the time is the same due to gravity and stability issues.

- **Assembly sequence**

Figure 4-10, 4-11 show that the type of assembly for the structural system and its elements restricts the disassembly potential and the time at which every element can be disassembled. At the time the assembly sequence can be generalized for the structural system. The next sections are going to discuss the type of connection and the geometry of element edge separately for each element.

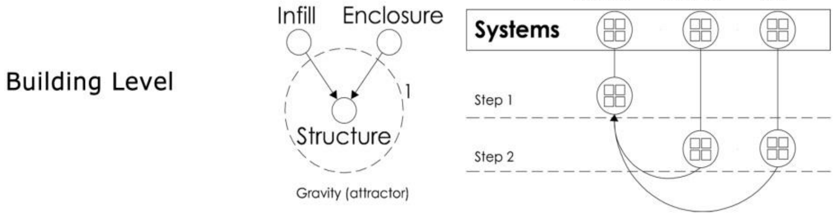


Figure 4-10: Type of assembly of the structural elements at the building level

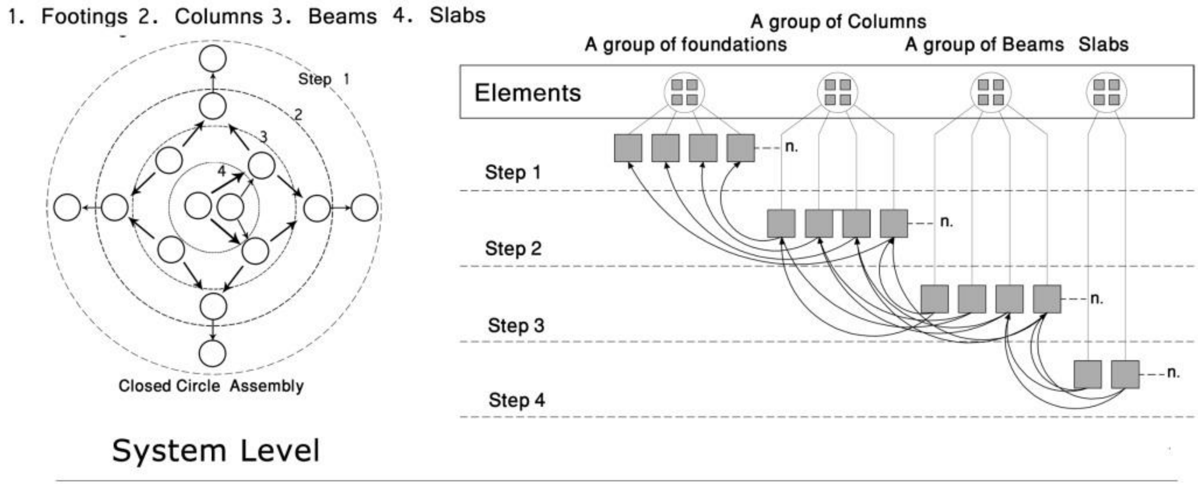


Figure 4-11: Type of assembly of the structural elements at the system level

- **Type of connection**

The type of connection for every element with the other elements at the system level in the structural system is a decisive factor regarding the disassembly potential of any element. Table 4-3 shows analysis of the common structural elements, their assembly and disassembly methods, the used type of connection and what hindrances could face the disassembly potential. It also shows the geometry of element edge of these elements.

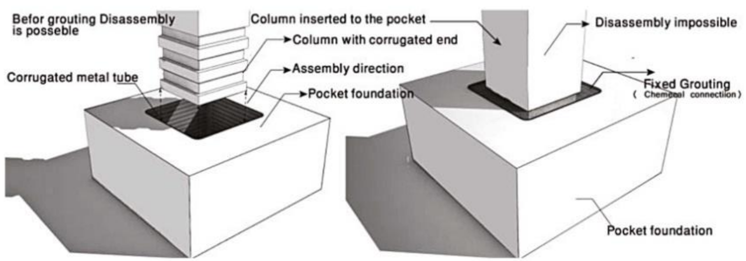
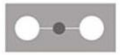
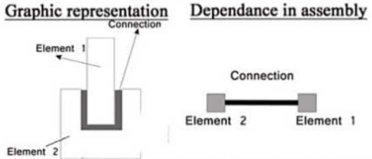
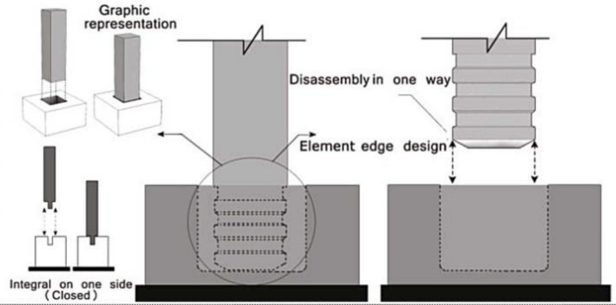
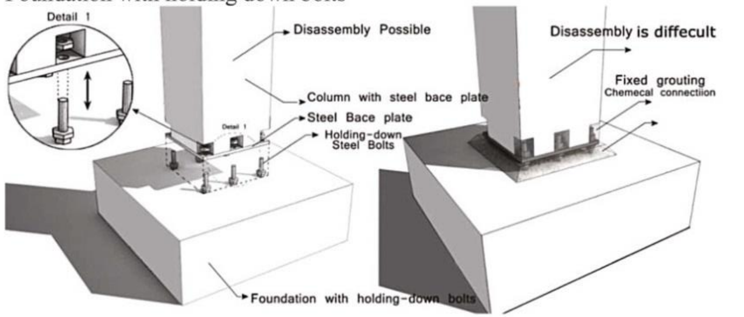
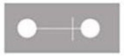
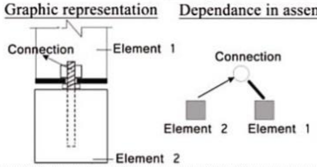
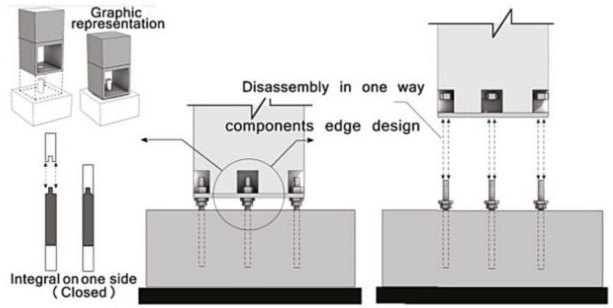
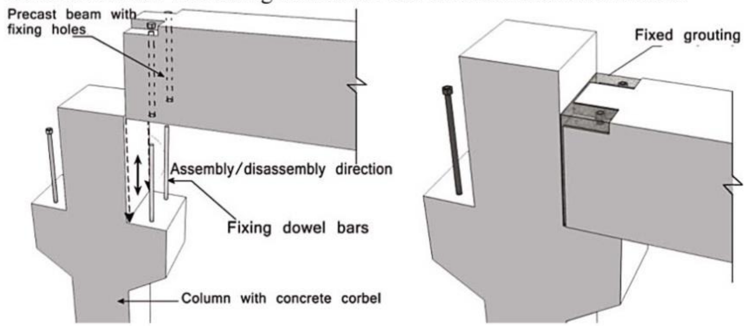
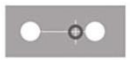
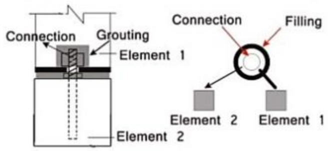
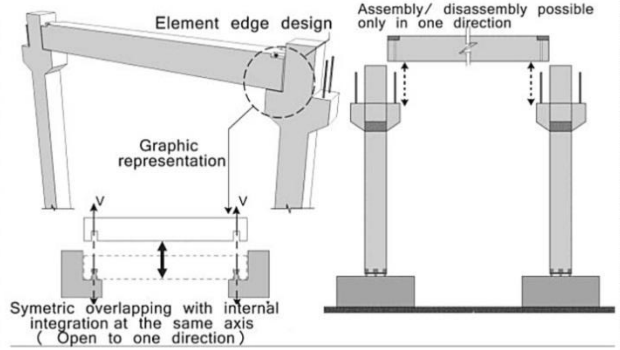
- **Geometry of element edge**

The geometry of element edge for any element or building product has an impact on the disassembly potential, especially the assembly sequence of elements. The geometry of element edge also is affected by the specification of the connection type. Table 4-3 shows the geometry of element edge for the common precast structural elements and their effect on the disassembly potential.

4.6.3 Evaluation of the disassembly potential of the structural elements

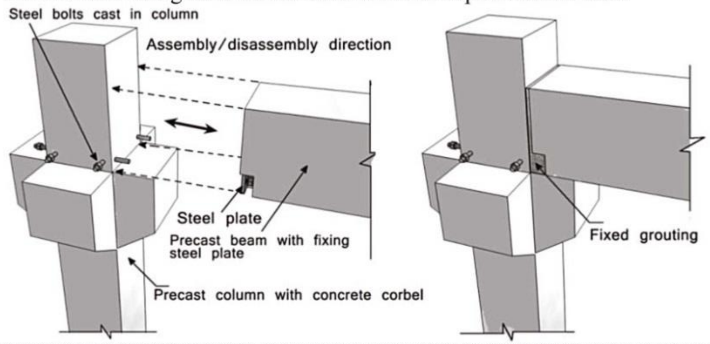
Based on the knowledge model of Durmisevic the disassembly potential of the structural system and its elements can be evaluated. This evaluation will show aspects of weakness that might cause time or material loss during assembly and disassembly of systems and elements. The indication of these aspects will provide developers with the potential to reconsider these aspects to reach high disassembly potential of systems and their elements (see table 4-3 and figure 4-12-18) (for evaluation details see appendix 13).

Table 4-3: The common precast elements of the structural system and their connection types and geometry of element edge

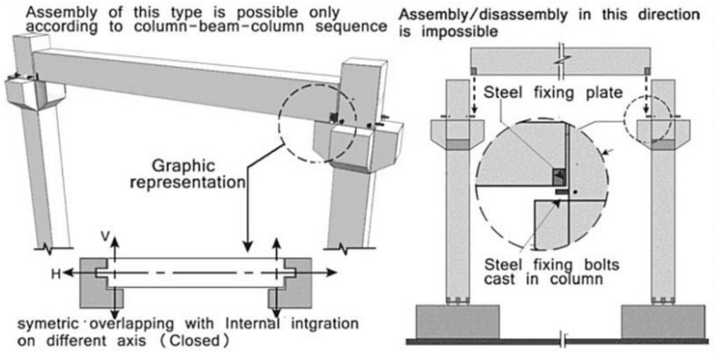
	Element	Connection type	Geometry of element edge
	Foundations		
1	Pocket foundation 	**Sign**  **Connection Type** Direct connection with third chemechal material. Tow elements are dependent in assembly/disassembly and chemically connected with a fixed material disassembly is impossible. **Graphic representation** **Dependance in assembly** 	
2	Foundation with holding down bolts 	**Sign**  **Connection Type** Direct connection with aditional fixing element. Tow elements are connected using steel bolts and nuts cast in an element and a steel base plate in the other element, dismantling of the nuts allow disassembly in one direction. **Graphic representation** **Dependance in assembly** 	
	Columns and beams		
1	Concrete corbels with fixing dowel bars cast in corbel and holes in beam 	**Sign**  **Type of connection** Direct connection with aditional fixing element blocked by filling. Tow elements are connected using steel bolts and nuts cast in an element and a steel base plate in the other element, Grouting is used which blocks acsses to the connection. (Disassembly is impossible) **Graphic representation** **Dependance in assembly** 	

2

Corbels with fixing bolts cast in column and steel plate cast in beam



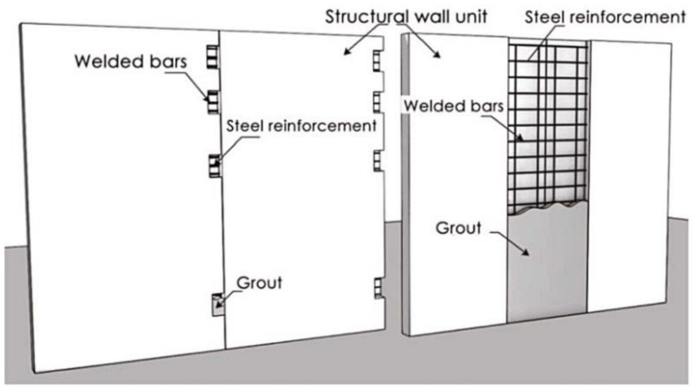
Same as previous



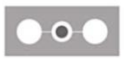
Structural walls

1

Jointed and monolithic structural walls



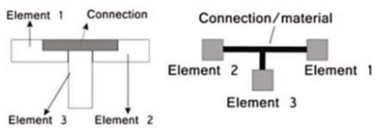
Sign

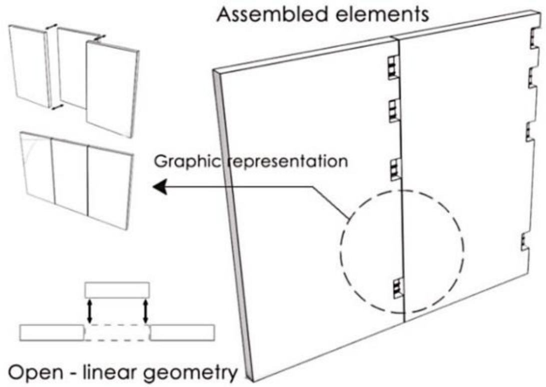


Type of connecion
Indirect connection with third chemechal material

Tow elements or more are independent in assembly/disassembly and chemically connected with a fixed material, disassembly is impossible.

Graphic representation **dependance in assembly**

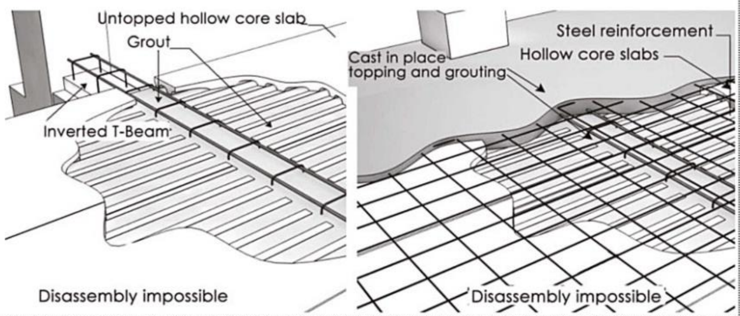




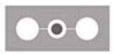
Spanning element

1

Hollow core slabs



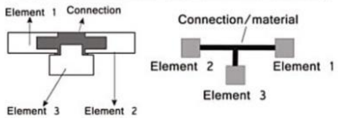
Sign

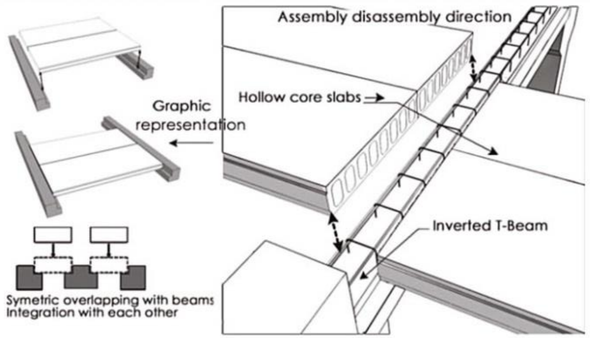


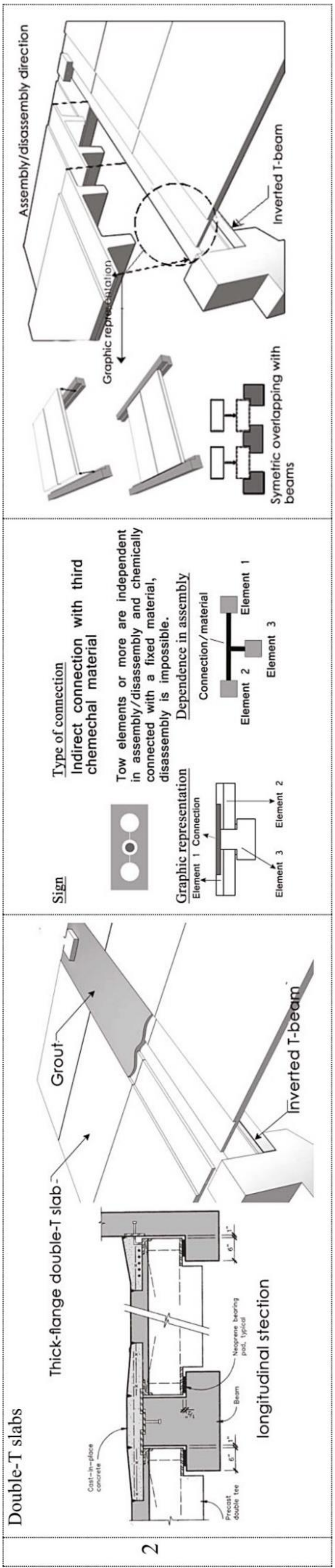
Type of connection
Indirect connection with third chemechal material

Tow elements or more are independent in assembly/disassembly and chemically connected with a fixed material, disassembly is impossible.

Graphic representation **Dependence in assembly**







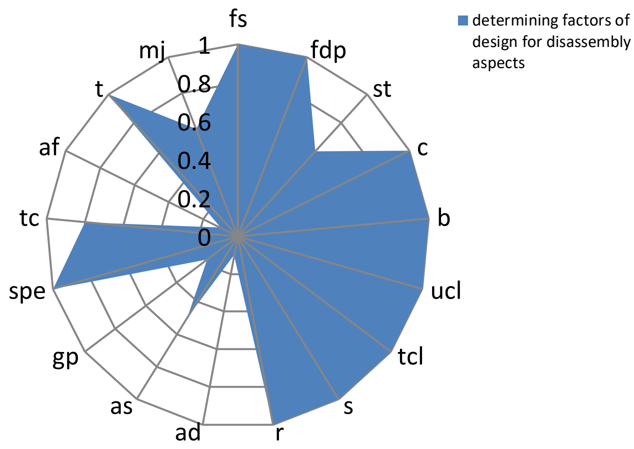


Figure 4-12: Radial diagram showing DfD aspects and their values for foundations with holding down bolts based on the model of Durmisevic

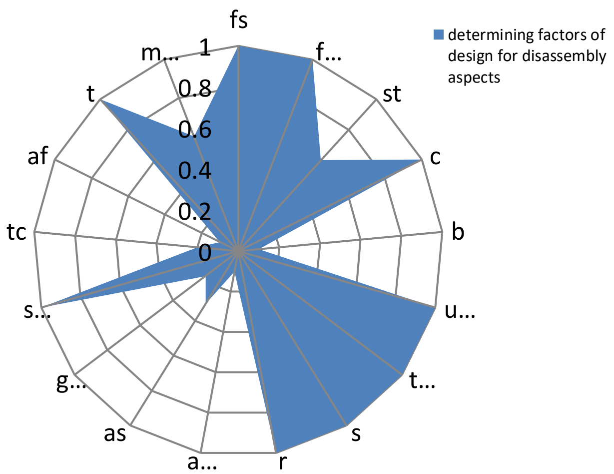


Figure 4-13: Radial diagram showing DfD aspects and their values for pocket foundations based on the model of Durmisevic

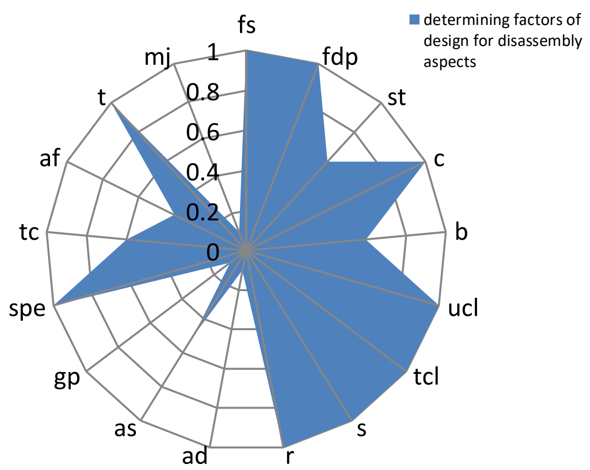


Figure 4-14: Radial diagram showing DfD aspects and their values for columns with concrete corbels and fixing bolts based on the model of Durmisevic.

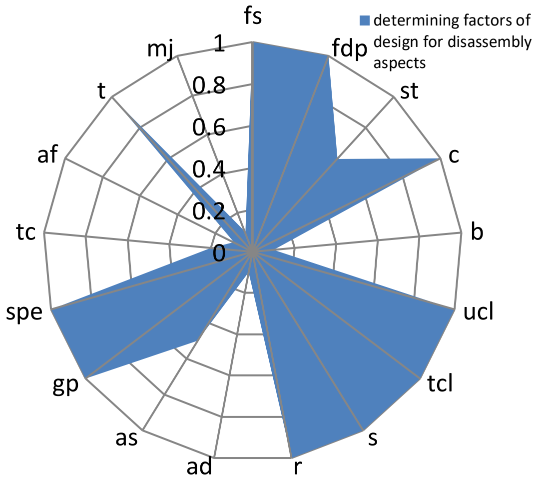


Figure 4-15: Radial diagram showing DfD aspects and their values for Structural walls based on the model of Durmisevic

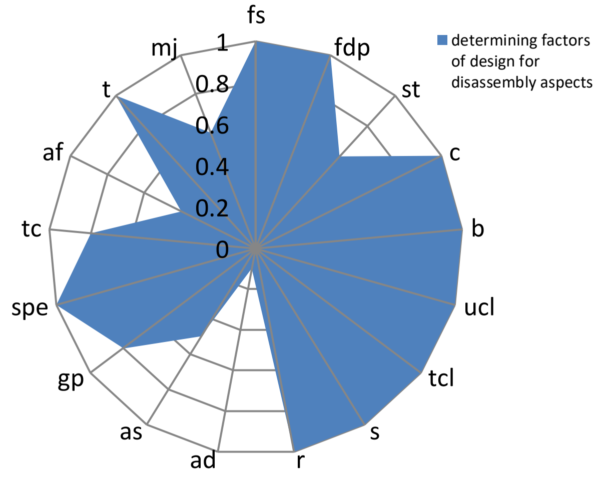


Figure 4-17: Radial diagram showing DfD aspects and their values for beams with fixing holes based on the model of Durmisevic

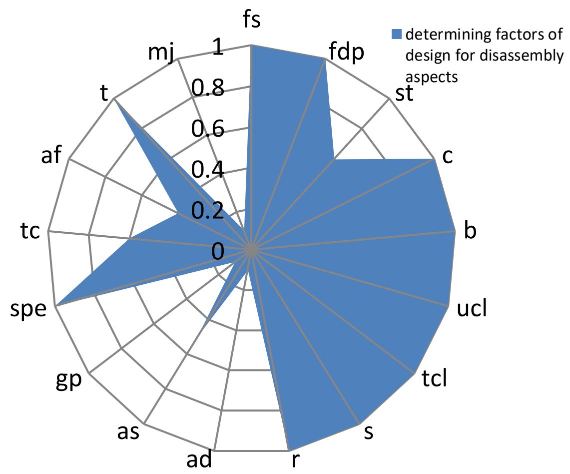


Figure 4-16: Radial diagram showing DfD aspects and their values for beams with fixing steel plates based on the model of Durmisevic

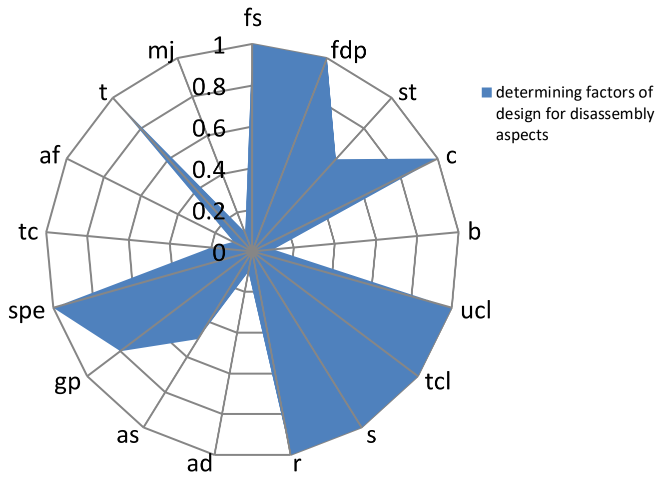


Figure 4-18: Radial diagram showing DfD aspects and their values for hollow core slabs seated on inverted-T beam based on the model of Durmisevic

The above figures provide clear indicators regarding the aspects that do not respond to the transformation capacity and the disassembly potential for each element of the structural system.

4.7 The Infill level of precast buildings

The infill system of any building is consisted mainly of partitions system and stairs system. Despite the fact that the infill system may include other things the focus will be on partitions and stairs as these systems could be made of precast concrete.

4.7.1 Physical system level and component/material level

This section reviews the most common precast elements of the infill system and their physical levels and material/component levels. It also provides an overview of the hindrances to their disassembly potential.

4.7.1.1 Precast partitions

However bricks and blocks walls could be forms of precast partitions since the primary elements are precast. The focus of this section will be on systems that might have some kind of disassembly potential. The review of precast concrete partitions shows that three main systems are common:

1 - Thin concrete layers and precast stud system

2 - Lightweight precast panels

3- Hollow core wall panels panel

Figure 4-19 shows the use of these systems and how it is built.

- **Thin concrete layers and precast stud system**

Precast studs are used to support two thin precast slabs (25-40 mm). Sound insulation is utilized between both sides of the slabs to improve the partition performance. The main connection material in this system is cement mortar which is difficult to be disassembled (Ecoursesonline, 2012).

- **Lightweight precast panels**

A number of precast light weight concrete wall types are produced to be used as partitions, these wall types include: "eps" sandwich panels and hollow core wall panels.

"eps" sandwich panels

Fiber cement boards are used as sandwich layers that enclose a core made of cement sand expanded polystyrene foam "eps", fly ash, water and additives. These panels are produced in length 4.55- 3.00 m and width of 0.60 m and thicknesses 60/75/90/120/150 mm. Cement mortar is mainly used to connect eps panels which produce permanent connections that are difficult to be disassembled (VANJOIN, 2014).

Hollow core wall panels

Concrete hollow core panels are used to construct partitions, the common dimensions are 2.70×0.6×0.12m. In addition to their lightweight these panels have also an excellent fire resistant. In this system also cement mortar is mainly used for the connections and the construction of panels which complicates the disassembly of panels (lightweightwallpanel.com, 2014-2016).

4.7.1.2 Precast concrete stairs

Precast stairs are produced in various types and sizes depending on the desired design. For common L-shaped and straight stairs various divisions could be found such as:

1. typical attached lower landing
2. typical attached upper landing
3. typical attached landings
4. stair flight

Various connection methods are used to construct precast stairs and fixing them to loadbearing structure. These connections range from steel connection with fixing bolts to permanent connection using cement mortar. In most cases a screed layer of mortar is used which covers the steel connection and prevents access to them (see figure 4-20) (Bison Concrete Product Ltd., 2008), (HY-GRADE: Precast concrete Ltd, 2015).

Figure 4-19: Various types of precast partitions.

4.7.2 Analysis of the disassembly potential of the precast infill system

Systems that have high disassembly potential could be reused, updated and reconfigured. The infill system is the one of the most systems that is exposed to change and updates as Duffy and Brand indicated when they conceived the building as a series of layers that have different life times (Salama, 2017). Also the continuous and rapid change of life required a kind of systems that supports change and reconfiguration. The following sections are going to consider analyses of the independence and exchangeability of material levels, technical composition and physical integration of the infill system and its common precast elements.

4.7.2.1 Material levels

The independence and exchangeability of material levels of partitions and stairs will be considered in this section. This analysis is supposed to add to understanding and help in the evaluation process.

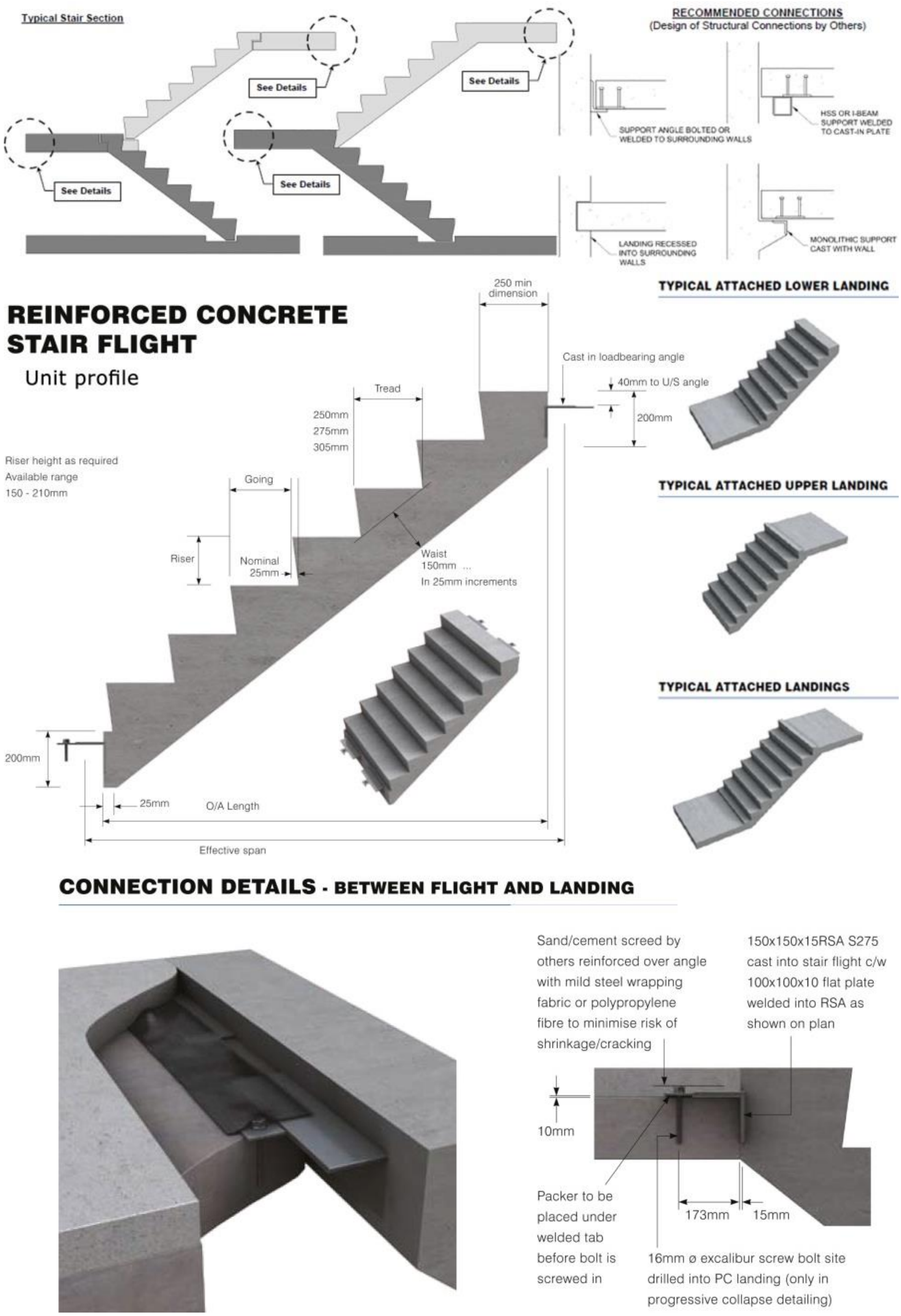


Figure 4-20: Common precast stair types and their connections

- **Precast partitions**

Partitions should enclose, separate and isolate spaces from each other's; these are the main function of partitions. However, the finish that is applied to these partitions provides the desired architectural appearance. The previous review showed that, two main types could be considered for analysis with regard to their material levels (see figure 4-21).

- **Precast stairs**

Precast stairs are used as support structures for vertical circulation in buildings. To improve the architectural appearance in most cases these stairs are supplied by a finishing material that range from marble to wood. The independence and exchangeability of these materials are important when considering design for disassembly (see figure 4-21).

4.7.2.2 Technical composition

The independence and exchangeability of the technical composition of the infill system should consider the hierarchal arrangements of material and relations between materials. Figure 4-22 shows the various technical composition properties for each system.

- **Precast partitions**

The relational pattern diagram shows that the common partition types have two different kinds of relations. One of these relations fulfill the independence and exchangeability requirements as in thin precast layers with studs system. And the other relational pattern shows that three functions have been interpenetrated into one monolithic element as in eps sandwich panels.

- **Precast stairs**

The hierarchal arrangement of materials and the relation between materials in precast stairs is simple, it also supports independence and exchangeability due to the direct relation between the loadbearing - which is the precast stair itself - and the finish material.

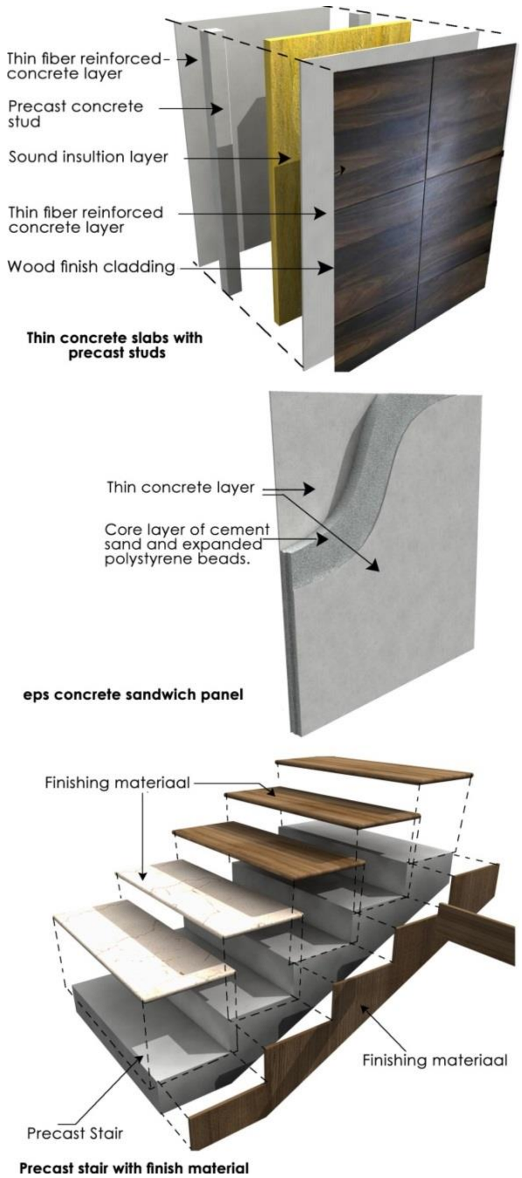


Figure 4-21: Material levels of various elements of the infill system

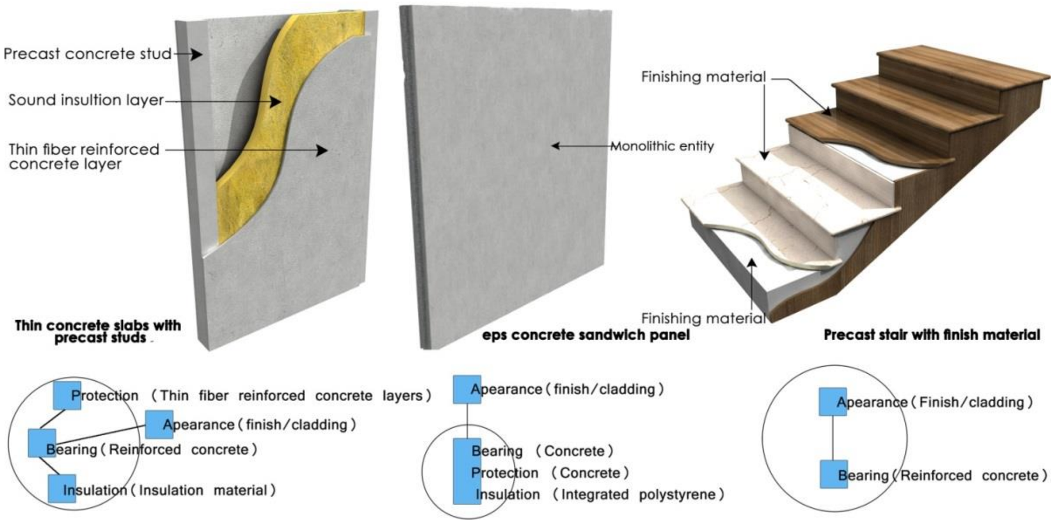


Figure 4-22: The technical composition of various elements of the infill system

4.7.2.3 Physical integration

As previously mentioned three main aspects decide the independence and the exchangeability of the physical integration. These aspects are as follows.

- **Assembly sequence**

Figure 4-23 shows the types of assembly for the infill system at the building level and the various infill elements at the system level.

- **Type of connection**

The types of connection for various infill elements are shown in Table 4-4. It can be noticed that the use of cement mortar in most cases is a hindrance to the demountability of systems and elements.

- **Geometry of element edge**

The geometry of element edge for various infill elements are shown also in Table 4-4and the following charts. It can be noticed that the use of integral in two sides for light weight panels restrict the assembly and disassembly process to a specific sequence.

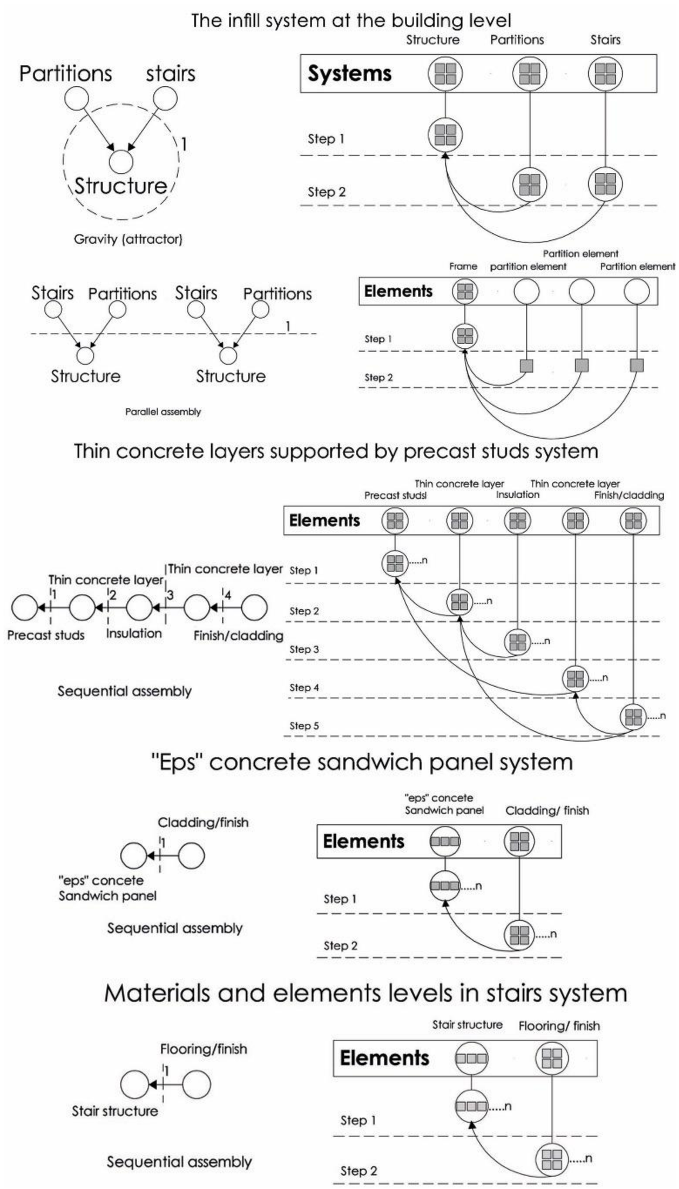
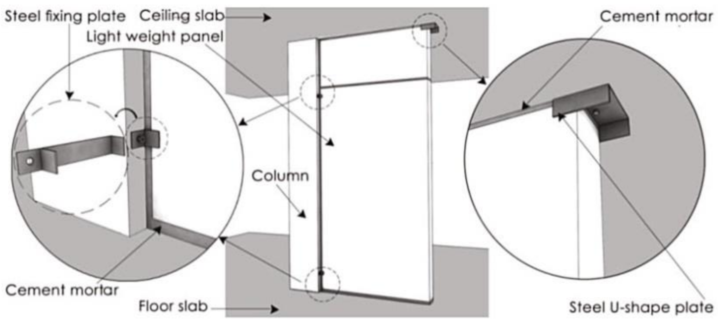
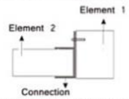
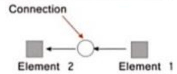
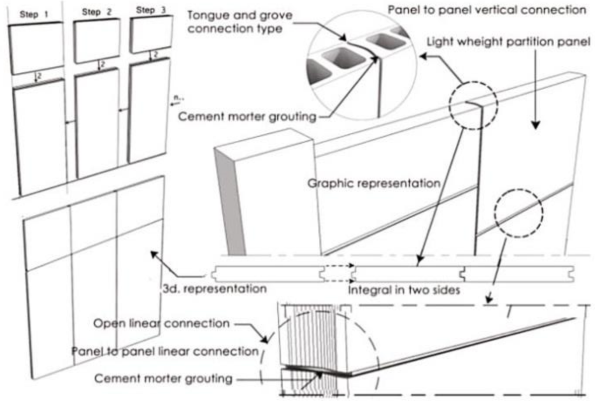
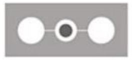
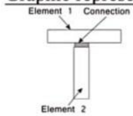
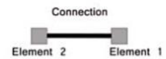
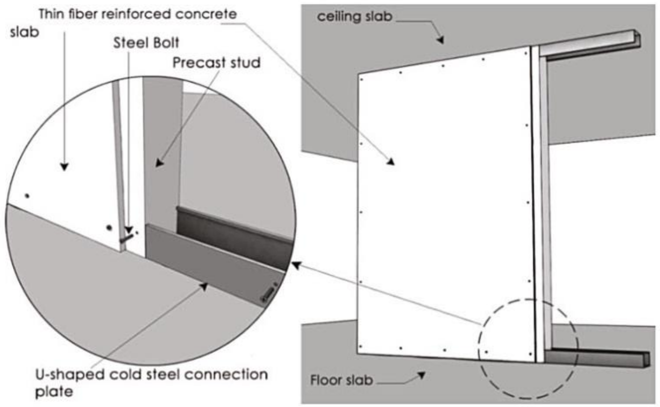
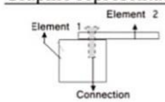
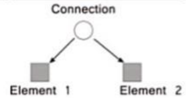
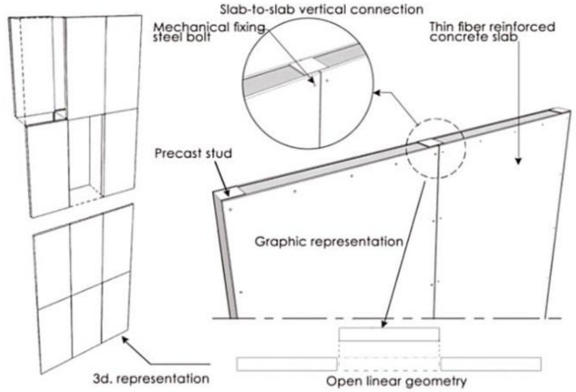
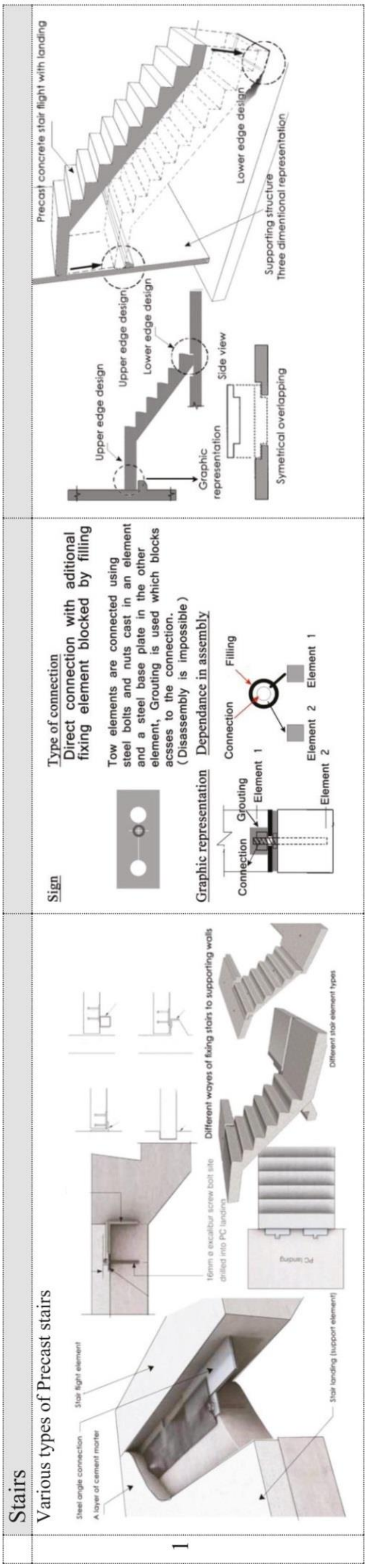


Figure 4-23: Types of assembly for various Infill system elements

Table 4-4: Connection type and geometry of element edge for various infill elements

	Element	Connection type	Geometry of element edge
	Partitions		
1	Lightweight panels 	**Sign**  **Type of connection** Indirect connection via dependent third component Tow elements are connected via a third component that depends on assembly/ disassembly sequence. **Graphic representation**  **Dependence in assembly** 	
		Sign  **Type of connection** Indirect connection with third chemichal material Tow elements or more are independent in assembly/disassembly and chemically connected with a fixed material, disassembly is impossible. **Graphic representation**  **Dependence in assembly** 	
	Thin concrete slabs with precast studs 	**Sign**  **Type of connection** Indirect connection via aditional fixing device Tow elements are connected via an adirional fixing bolt which can be dismanteled. **Graphic representation**  **Dependence in assembly** 	



4.7.3 Evaluation of the disassembly potential of the infill system

Table 4-4 shows the evaluation of the disassembly potential of the infill system and its elements based on the knowledge model of Durmisevic (for evaluation details see appendix 14).

The figures below indicate aspects that do not respond to transformation capacity and disassembly potential requirements for each element of the infill system.

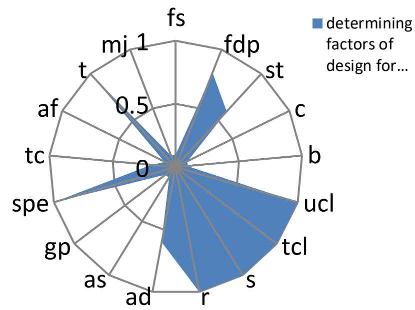


Figure 4-24: Radial diagram showing DfD aspects and their values for the lightweight partition panel type at worst case based on the model of Durmisevic

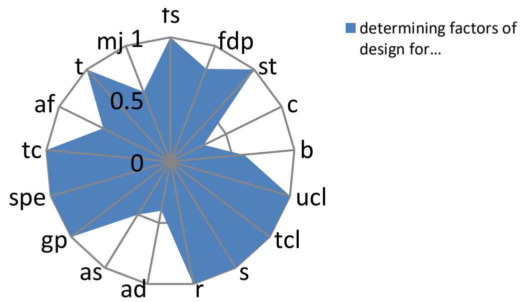


Figure 4-25: Radial diagram showing DfD aspects and their values for thin precast concrete slabs with precast studs based on the model of Durmisevic

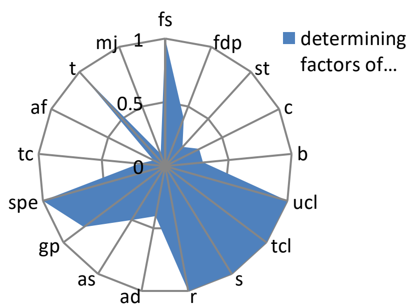


Figure 4-26: Radial diagram showing DfD aspects and their values for precast stair system at worst case based on the model of Durmisevic

4.8 The enclosure level of precast buildings

This section mainly focuses on the precast concrete facades. The characteristics of facades is determined by the architectural requirements and building physics which give the facades its architectural aesthetics and the interior its suitable environment. Facades do an important function on the building level. It not only provides the building with the architectural aesthetics but also protects, isolates and insulates the interior.

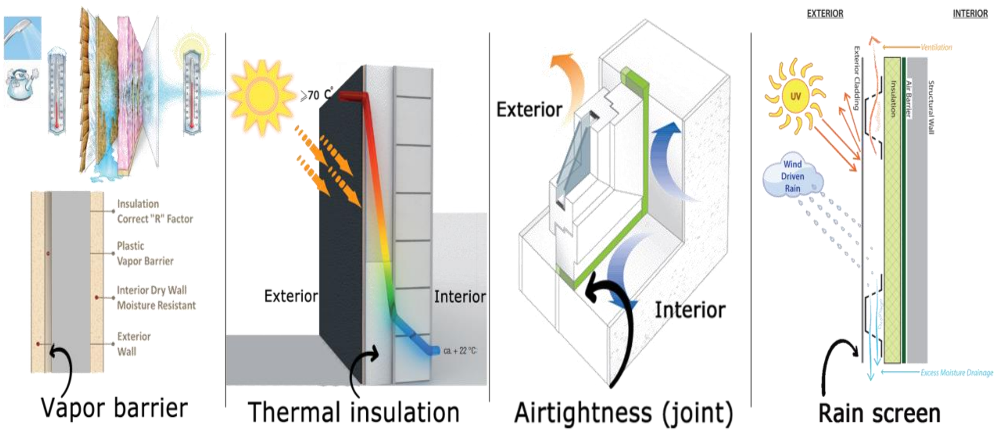


Figure 4-27: Climate influences on facades and their solutions (GIBSON, 2010), (Brillux, 2015) (Tremco, 2015), (Tom & P.E, 2013)

4.8.1 Physical system level and component/material level

This section explores and reviews the most popular precast facades and shows their physical system level and component/material levels. It also provides a brief overview of the hindrances to their disassembly potential and transformation capacity.

4.8.1.1 Types and design of precast concrete facades

Four main categories of precast facades are commonly used around the world. These categories are as follows (Anderson & Anderson, 2007), (Bachmann & Steinle, 2011), (PCI P. , 2015):

1- Sandwich or composite panels
2- Conventional panels
3- Cladding panels
4- Hybrid thin-shell precast wall systems (such as fiber reinforced concrete panels anchored to a cold-formed galvanized steel frame and IHI composite panel structure by IHI Corporation, Canada).

Precast concrete facades can be designed using various segmentations and shapes where that main goal of these designs in addition to the architectural appearance is to provide fast assembly and cost efficiency. Some facades are being designed to have load bearing characteristics (see figure 4-28) (Bachmann & Steinle, 2011).

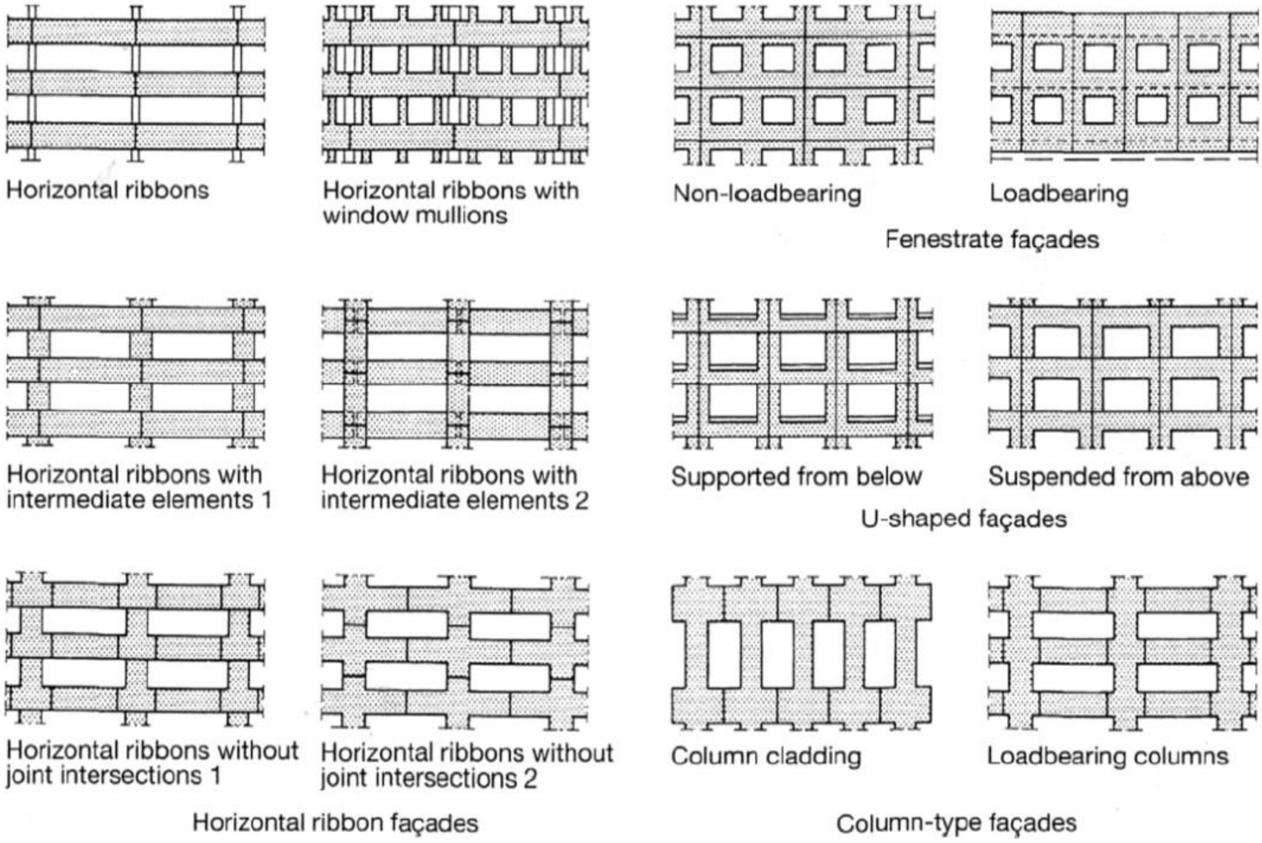


Figure 4-28: Various designs of precast facades

- **Precast sandwich panels**

Considered one of the most used types of precast panels due to the speed of construction where these panels provide the most functions that are required from façades. Precast concrete sandwich panels consisted of two layers of reinforced concrete and a layer of thermal insulation material in between.

Figure 4-29: Various designs of loadbearing facades

The two concrete layers are connected using either steel or glass fiber connectors. Electrical services are usually integrated to the interior concrete layer by providing plastic pipes. It is possible to provide the exterior layer of the sandwich panel with a specific finishing material or cladding or shapes using predesigned molds (PCI, 2012). In most cases these panels are connected and jointed using cement mortar which make the demountability of these panels without damaging the panels edges very difficult. It is also important to mention that the disassembly of these panels to its material levels is very difficult.

Side view cut-away samble New type of Sandwich panels presented in Bauma 2016, Munich Vertical section

Figure 4-30: Sandwich panel system

- **Conventional panels**

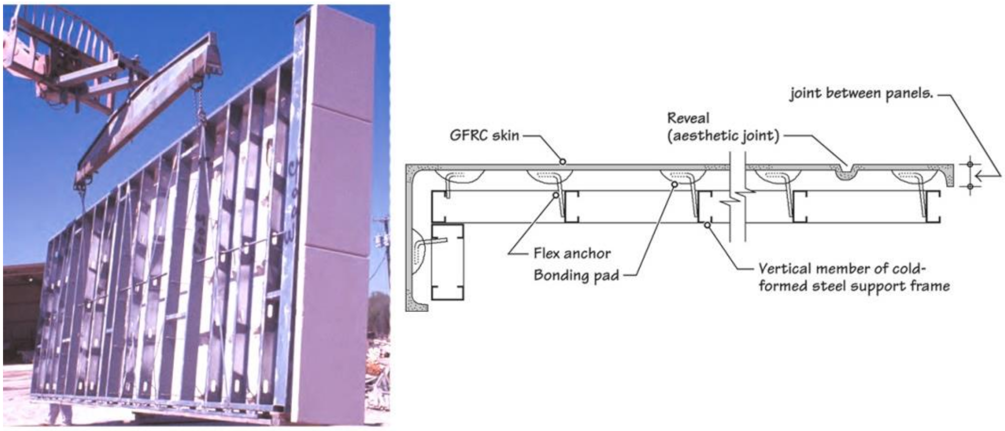
Conventional panels are the simplest form; they are consisted of a single layer of concrete usually used in the exterior side. Another interior layer is required where an insulation material is added to the exterior side of this layer. This interior layer is usually made of steel gauge and dry wall boards (CMHC, 2002). In general, the conventional precast panels can be easily disassembled especially when the cement mortar is avoided. However, the geometry of element edge design in some cases and the type of connection restrict the disassembly of these panels.

Construction of conventional precast panels Various finishing Vertical section

Figure 4-31: Conventional panel system

- **Hybrid thin-shell precast wall systems**

Fiber reinforced concrete is used to make strong thin-shells that are anchored to steel frames and can be used as exterior facades. These facades usually required a second interior part of steel studs, thermal insulation and dry wall panels (Mehta, Scarborough, & Armpriest, 2012).



Hybrid thin-shell facade system

Horisontal section

Figure 4-32: Hybrid thin-shell system

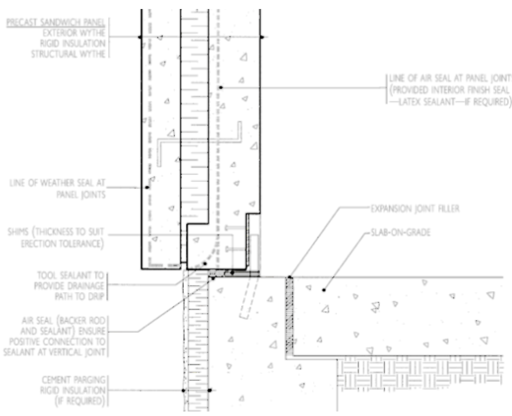
- **Cladding panels**

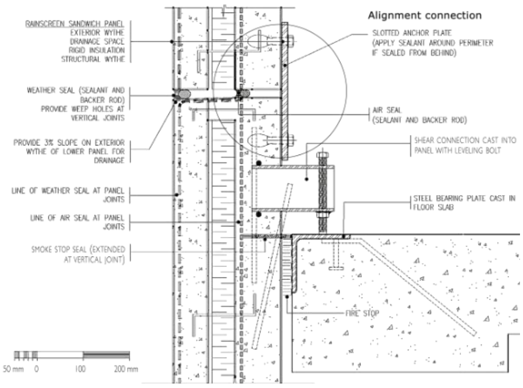
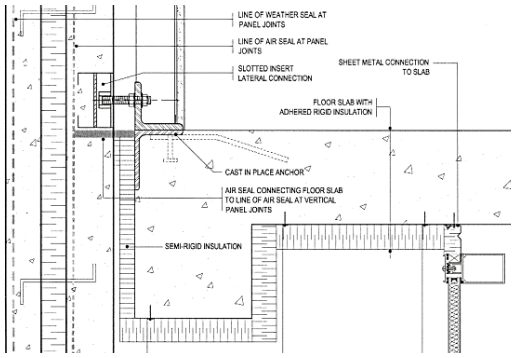
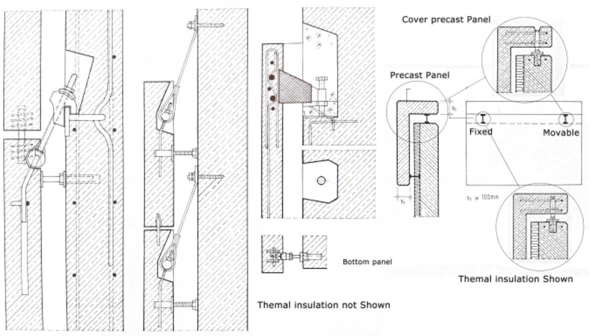
Cladding panels differ from the previously mentioned panels mainly by their thickness and size where they are mainly used for architectural aesthetic purposes. When some kind of finishes such as brick are used the thickness of these panels increases. In most cases these panels are fixed to cast-in-situ concrete facades after addition of a thermal insulation layer (Mehta, Scarborough, & Armpriest, 2012). The disassembly of these panels depends mainly on the jointing methods and connection types which in most cases follow a sequential assembly that restricts the disassembly process.

4.8.1.2 Anchorage and connections

Precast facades are attached and anchored to the building frame using a wide range of connections that are responsible for the stability and assembly of these panels. The main function of these connections is to transfer loads of the panels in addition to wind and expected seismic movements. The most common connection types are as in table 4-5

Table 4-5: Main types of precast panels connections

<table>
<tr><td></td><td></td><td></td></tr>
<tr><td>1</td><td>Direct bearing connection

</td><td>The main function of this type is to transfer loads of the panel to the supporting structure, direct bearing connections used as well for self –supporting panels to transfer vertical loads where tie back connections are used for lateral forces.
Normally two bearing connections are enough for an individual panel (CMHC, 2002).</td></tr>
</table>

2 3	Eccentric bearing connection Alignment connection  	This type usually used above support level and could be made of steel or reinforced concrete. Alignment connections are used mainly for connecting two precast panels together in an aligned manner (CMHC, 2002).
4	Tie back connection  	The main function of this connection is to support the panel and retaining it in the required position, it also resists wind and seismic loads. Usually two to four laterals ties back connections are used for individual panel. Sometimes additional wind connections are required (CMHC, 2002).
4	Cladding connection solutions  	Various types of steel cladding connections are commonly used to support various cladding materials such as: grout-in anchors, adjustable and suspended connections (Halfen, 2014).

4.8.1.3 Jointing facades

The joint in general is the internal gap between adjacent elements or between an element and other part of the structure (NPCAA, 2015). The importance of jointing the facades comes from the fact that suitable and perfect jointing play an important role in completing the function of the building envelope and prevent from unwanted penetrations of wind and water. Various methods of jointing are commonly used using various jointing material, all of which provide the same function (Bachmann & Steinle, 2011). The following are the common jointing techniques and materials:

1. Elastic sealant compounds
2. Drained joint
3. Waterproofing with adhesive strips
4. Joint waterproofing with pre-compressed sealant strips

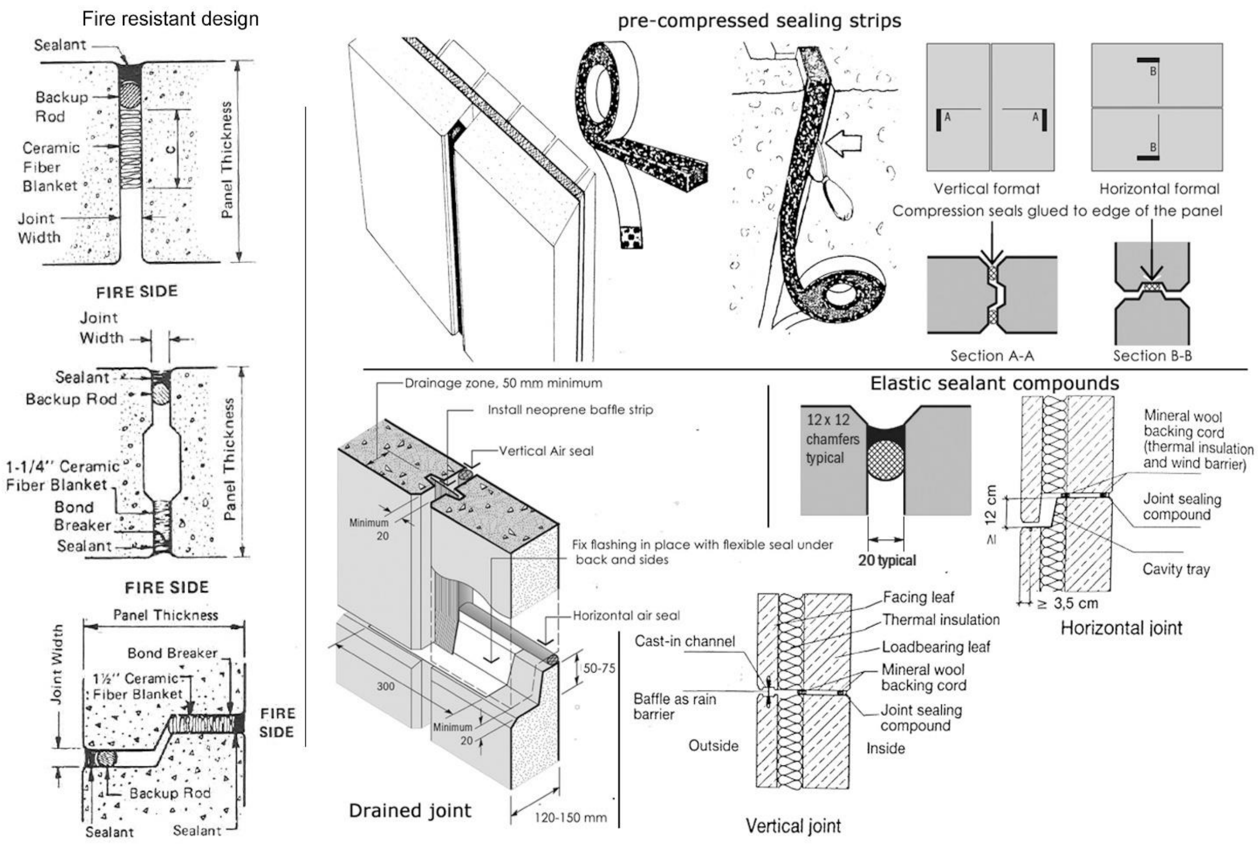


Figure 4-33: Common jointing techniques

The wrong application of jointing materials and techniques is the major cause for joint failure and problems, especially when we know that most of jointing material manufacturer provides garantee for a long period of time as shown in (Appendix 15).

4.8.2 Analysis of the disassembly potential of the enclosure system

The desire to change the appearance of a building through its facades could come to the mind of any building owner due to a number of reasons. These reasons may include obsolescence, adaptability or upgrade. Since the change required the ability to demount the old facades this study provides a detailed analysis of the disassembly potential for the most common façade panel systems. This analysis will provide the developers of façade systems with a complete picture regarding the design aspects that shape a hindrance to their demountability and reuse.

Due to the multiple functions that the facades provide, concrete facades should have other materials than concrete. Insulation, finishing and services are important parts that every façade should accommodate. The independence and exchangeability of these parts or material levels makes their disassembly for reuse or replacement possible.

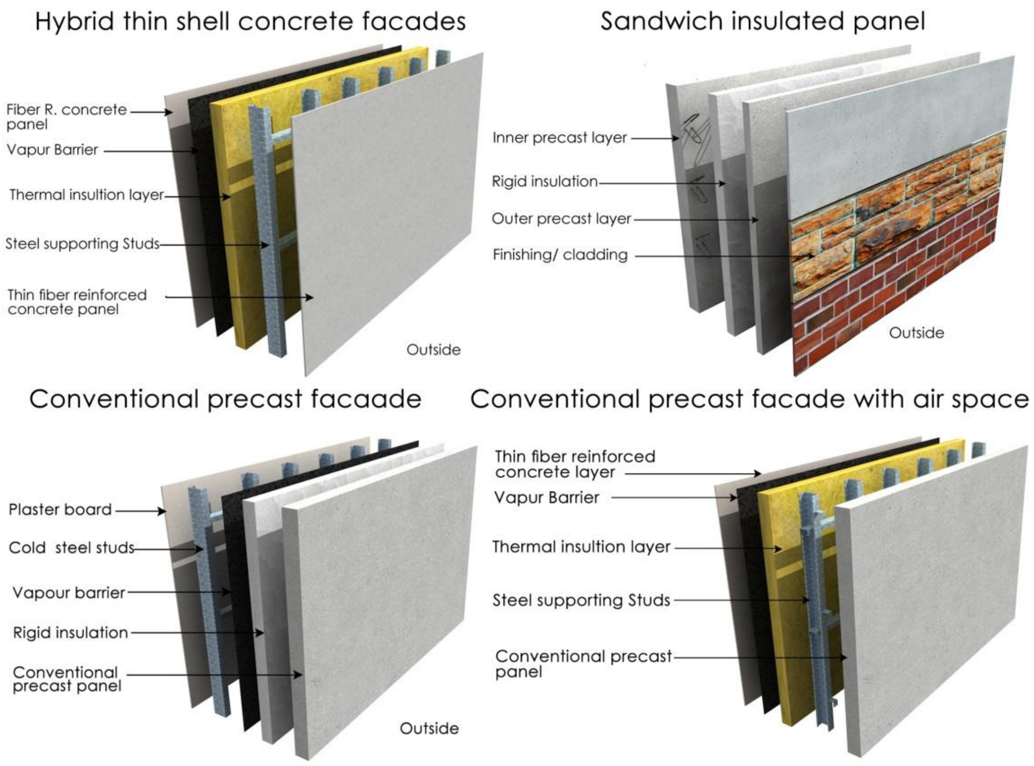
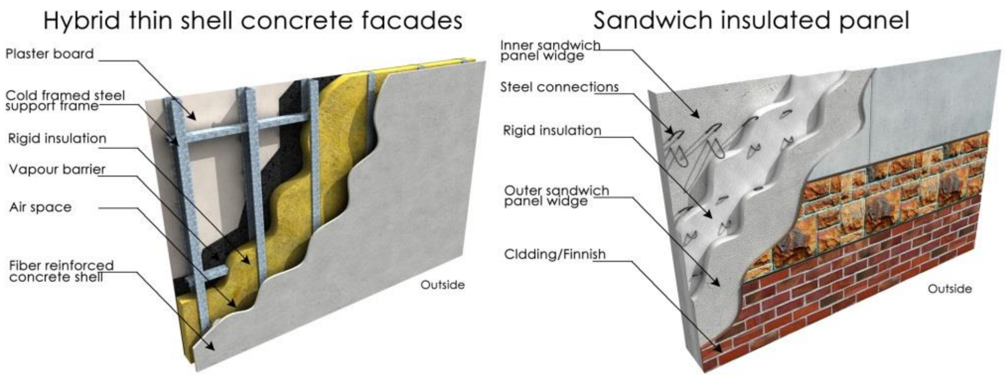


Figure 4-34: Material levels for various precast facades systems

It is clear that in most cases the disassembly of these façade systems to their material levels is difficult due to the use of conventional construction methods. The current construction design of these systems also restricts the disassembly options to demolition. The interior part that includes normally dray walls and light steel studs have no option except demolition. The use of permanent connections in sandwich panels also prevents from disassembly of the system to its material level.

4.8.2.1 Technical composition

The hierarchal arrangement of materials and the relations between materials and the level of their independence and exchangeability is shown in figure 4-35



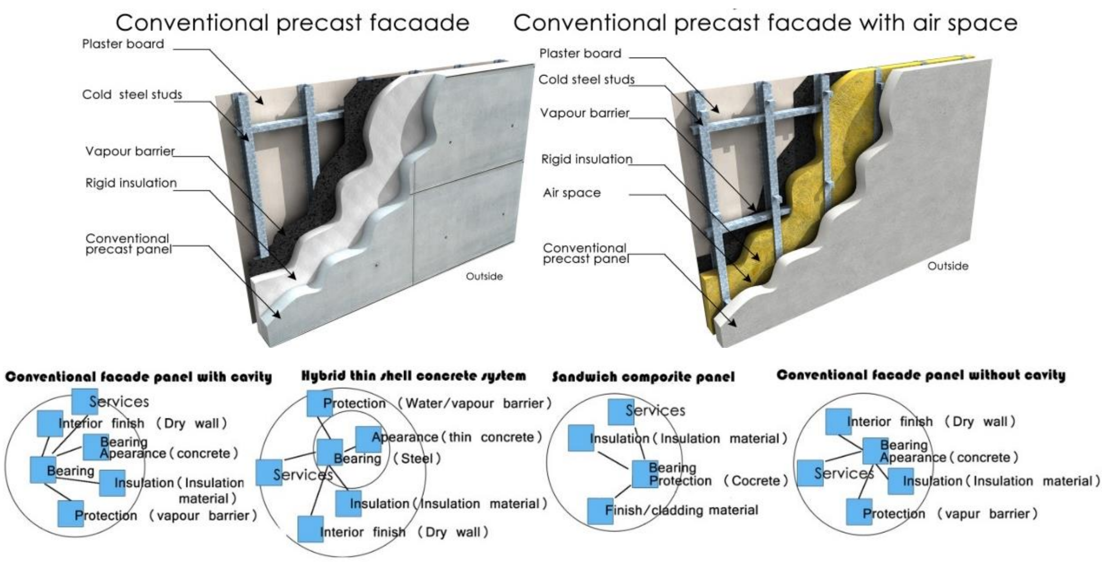


Figure 4-35: Arrangements of materials and relations between functions in common precast façade systems

It can be noticed that concrete does multiple functions such as bearing and protection, furthermore it provides the building with the exterior appearance. However, concrete provides load bearing and protection at the same time, the appearance - which is the finish of panels - might have higher exchangeability rate and should be separated. It can be also concluded that the arrangement of materials provides the required independence and the demountability. It can be noticed also that the problem in facades case is mainly the conventional method of construction that prevent from separation of façade panels and material levels.

4.8.2.2 Physical integration

The independence and exchangeability of the physical integration of the concrete facades is determined by the assembly sequence, the type of connection and the geometry of element edge. The following sections discuss the physical integration aspects for common precast façade systems.

- **Assembly sequence**

Precast facades usually follow the gravity (attractor) assembly since it is supported by the structure of the building. At the same time facades elements can be assembled in a parallel sequence for sandwich panel system and sequential sequence for conventional panels at the building level. At the system level assembly sequence of the various systems differ as in figure 4-36.

- **Type of connection**

Two main types of connection can be distinguished in precast panels, façade-to-structure connection, and panel-to-panel connection. These connections most of the time are demountable since steel bolts and plates are used. In cases of direct bearing connections when cement mortar is used the disassembly of façade panels becomes difficult and damaging.

- **Geometry of element edge**

Three main types of geometry of element edge are commonly used in precast concrete façade panels: open linear geometry, unsymmetrical overlapping and integral on two sides.

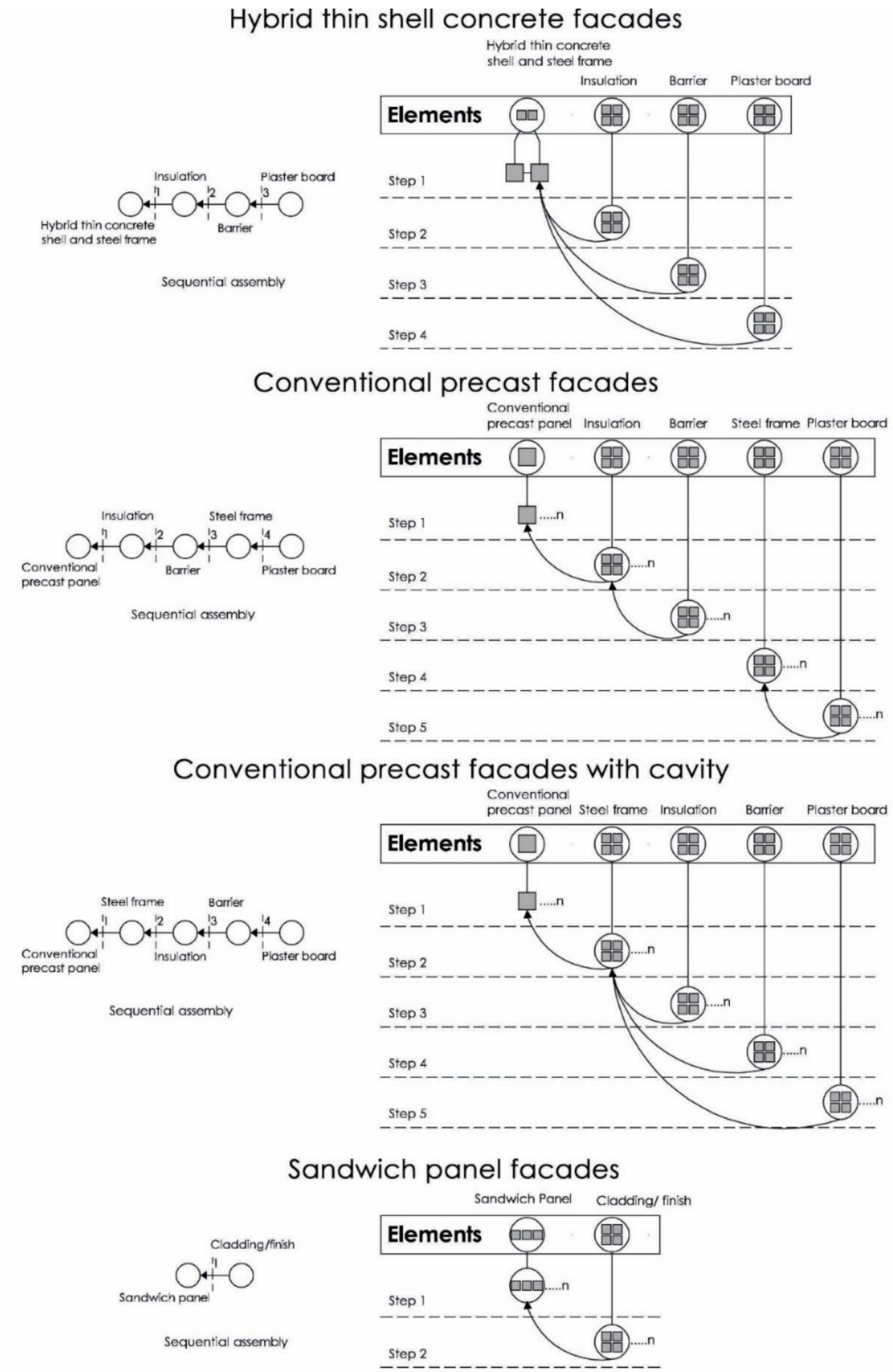
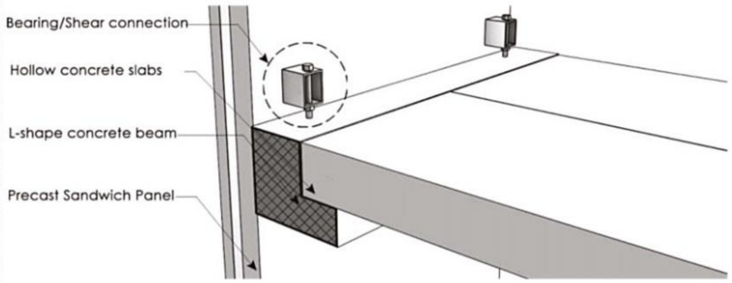
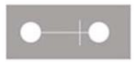
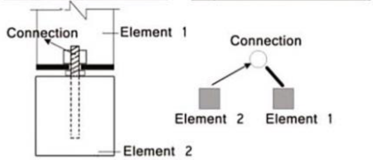
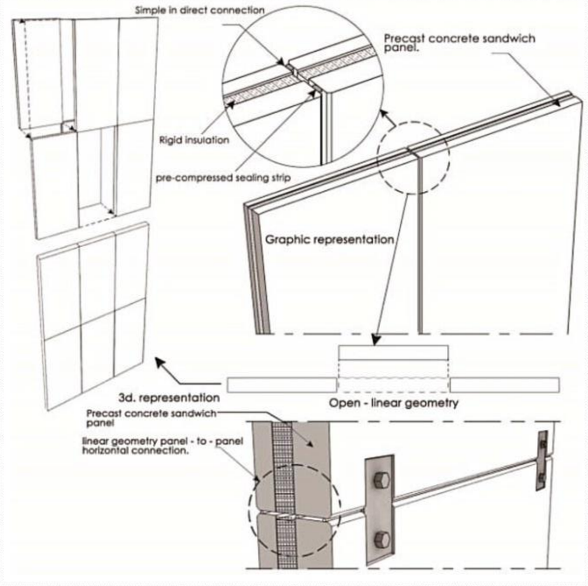
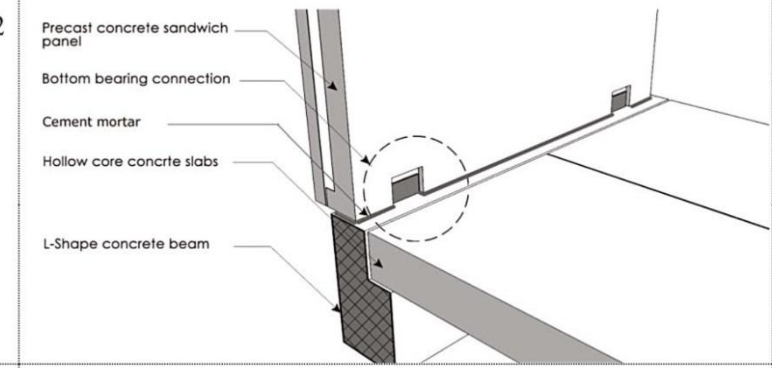
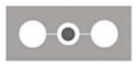
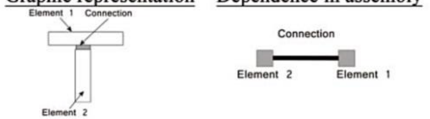
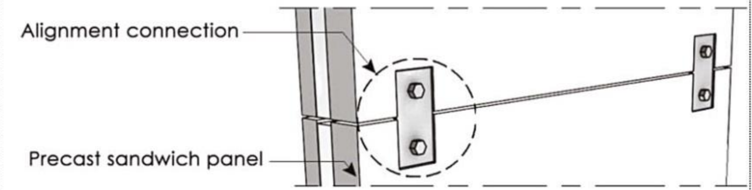
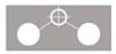
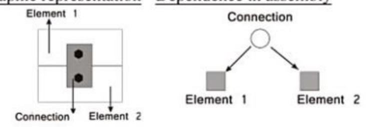
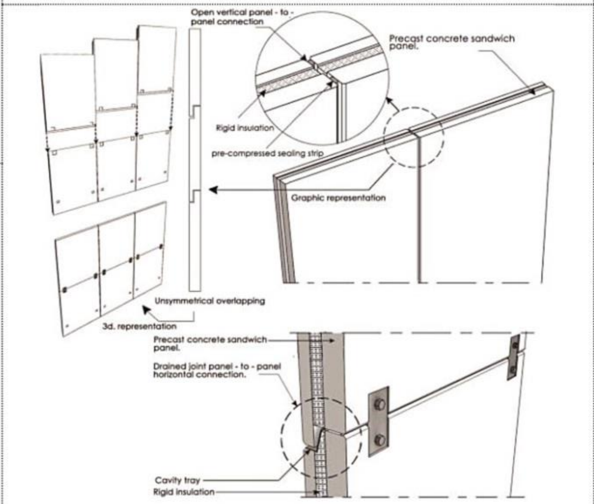
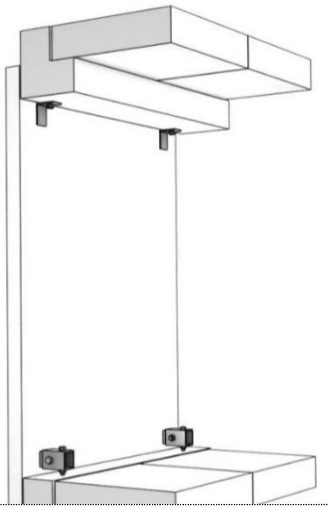
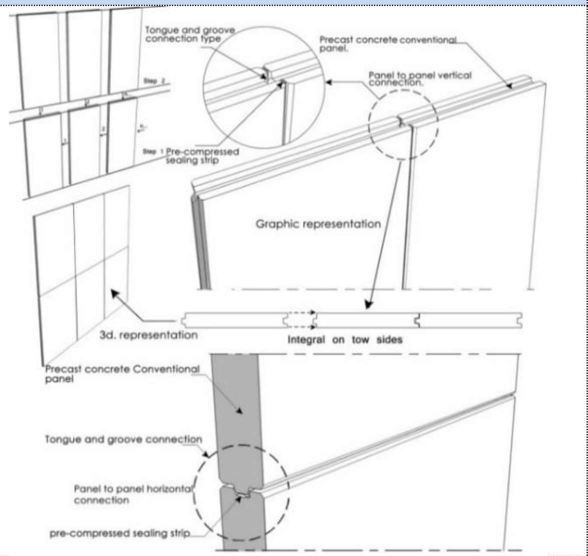
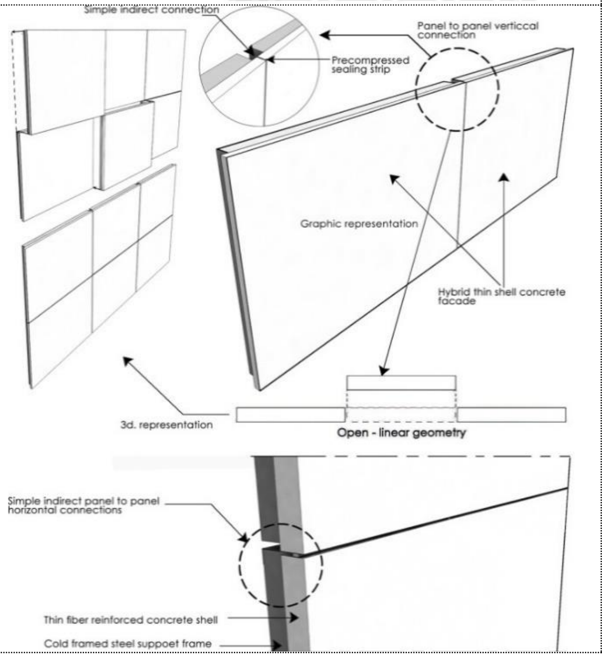


Figure 4-36: Types of assembly sequence for various facade systems at the system level

Table 4-6: Analysis of the types of connections and geometry of element edge for common precast facades

	Element	Connection type	Geometry of element edge
	Façade panels		
1	Sandwich panels  	Sign  Connection Type Direct connection with aditional fixing element Tow elements are connected using steel bolts and nuts cast in an element and a steel base plate in the other element, dismantling of the nuts allow disassembly in one direction. Graphic representation / Dependance in assembly  	
2	 	Sign  Type of connection Indirect connection with third chemichal material Tow elements or more are independent in assembly/disassembly and chemically connected with a fixed material, disassembly is impossible. Graphic representation / Dependence in assembly  	
3	 	Sign  Type of connection Indirect connection via independent third component Tow elements are connected via a third component which can be dismanteled, befor dismantling of the third com Graphic representation / Dependence in assembly  	

<table>
<tr><th></th><th></th><th></th><th></th></tr>
<tr><td>1</td><td>Conventional panels
</td><td>The same connections as previous</td><td>
</td></tr>
<tr><td></td><td>Hybrid thin-shell concrete facades
</td><td>The same as previous</td><td>
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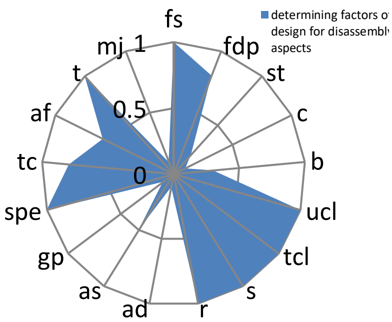


Figure 4-37: Radial diagram showing DfD aspects and their values for conventional panel types (the worst case) based on the model of Durmisevic

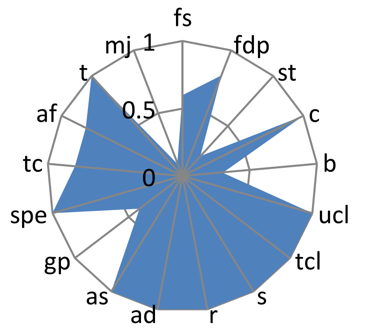


Figure 4-38: Radial diagram showing DfD aspects and their values for the sandwich panel based on the model of Durmisevic

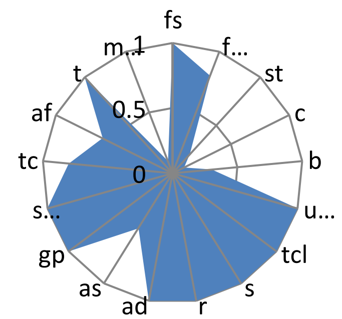


Figure 4-39: Radial diagram showing DfD aspects and their values for fiber reinforced concrete facades based on the model of Durmisevic

4.8.3 Evaluation of the disassembly potential of the facade systems

Figure 4-37 -39 shows the evaluation of the disassembly potential of the various facade systems based on the knowledge model of Durmisevic (for evaluation details see appendix 16).

The figures above indicate aspects that do not respond to transformation capacity and disassembly potential requirements for each façade system.

4.8.4 Results and discussion

The previous analysis provided a complete picture regarding limitations and potentials of the studied elements concerning their material levels, technical composition and physical integration. Such analysis could not only help in performing the proposed evaluation but also help in providing manufacturers - who want to develop their products to have higher disassembly potential - with an integrated perspective. The evaluation also indicated the design for disassembly aspects and their determining factors that need more attention when developing these products for demountability.

4.9 Conclusion

The following points can be concluded:

1. Separation of functions and emancipation of material levels of concrete buildings could be achieved through precast systems. In this case the technical composition of the building should include separation of building levels, their physical system levels in addition to component and materials levels.
2. Identifying the use strategy of the building could help in deciding the level of disassembly at the building level when the grantee of reusability of elements is required.
3. The structural level of precast buildings and its elements could have medium to high disassembly potential. Despite the previous fact the assembly sequence and the gravity requirements restrict the transformation capacity of this system.
4. In most of the structural elements the use of cement mortar to cover steel connection disables the accessibility to fixing.
5. Due to the unique function of the structural system the systematization aspects could be generalized for the common elements.
6. The use of cement mortar for light weight partition panels is not the only aspect that results in their low disassembly potential.
7. Due to the special role of facades and their contribution to the architectural value, in addition to the various functionalities and the use of different material levels design of concrete facades for disassembly and reuse will increase their value.
8. The common precast concrete facades showed medium to high disassembly potential; however, they still need to be considered regarding their weak aspects.

Chapter 5. Achieving high disassembly potential of the precast concrete facades (systems development)

Introduction

Concrete is still a preferable material for facades due to several reasons. Durability, the ability to take any form, strength, availability, thermal mass and the wide usage around the world are some characteristics of concrete. Concrete can provide the most façade functionalities such as protection, loadbearing, appearance, fire resistance and sound transition resistance. Only the resistant to heat transition is not satisfied by concrete (Bachmann and Steinle 2011). This chapter takes into consideration the previous study, analysis and evaluation of the concrete facade systems with regard to their disassembly potential. It considers developing of areas that show low disassembly potential to have higher ones. As discussed before, the evaluation included seventeen determining factors that not only determine the level of disassembly of a specific system but also its transformation capacity. The following pages will include some proposed concepts for the development of systems. It is important to remember that these concepts and designs tend to raise the disassembly potential of the existed systems in order to allow adaptability, upgrade and reuse of their elements and materials.

Two common precast façade systems including conventional panel and sandwich panel have been considered and developed by introducing DfD aspects. These aspects guarantee in addition to fast assembly and disassembly of the system and its material levels a high reuse potential. In addition to that the recovery and reuse options for these systems and their elements have been identified.

5.1 Development of the precast concrete conventional panel system

The previous analysis of the precast concrete conventional panels has shown that this system has a medium disassembly potential based on the evaluation model of Durmisevic. The figure to the right indicates that the system has not satisfied high disassembly potential requirements, due to the low scores that some determining aspects achieved. These aspects have been marked by red circles including:

- st: structural and material levels
- c: clustering

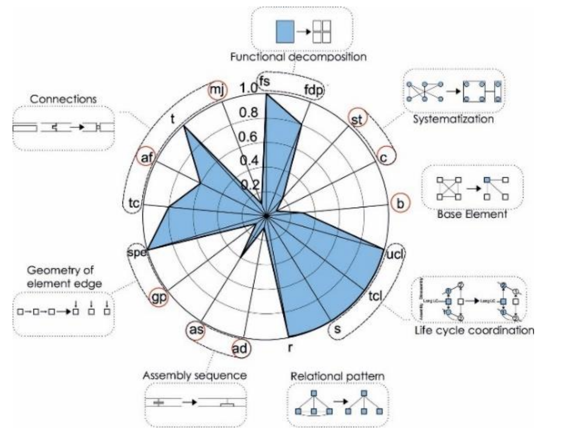


Figure 5-1: Evaluation chart of precast concrete conventional panel showing areas of low transformation capacity.

- b: base element specifications
- ad: assembly direction
- as: assembly sequence regarding material levels
- gp: the geometry of element edge
- af: accessibility to fixing
- m: morphology of joint

It can be noticed that precast concrete conventional panels lack high transformation capacity regarding aspects of systematization, base element specifications, assembly, the geometry of element edge and some connections aspects. To provide this system with a high transformation capacity and disassembly potential the following developments are going to be applied.

5.1.1 Systematization development

Achieving high disassembly potential of precast concrete conventional panels required the development of their weak aspects. The analysis and evaluation of this system have shown that this system required a number of construction operations after installing the conventional precast panels. These operations include installation of insulation materials, bearing studs for the interior finish, vapor barrier, and the interior drywall or a specific architectural interior finish. These operations occurred on site which increases assembly time and complicates the future disassembly. The following developments consider systematization of these systems materials and elements to provide suitable solutions that lead to a higher disassembly potential. Table 5-1 indicates the design for disassembly aspects that needs to be developed and the propsed solution for systematiztion issues.

Table 5-1: Development of systematization aspects for conventional precast panels

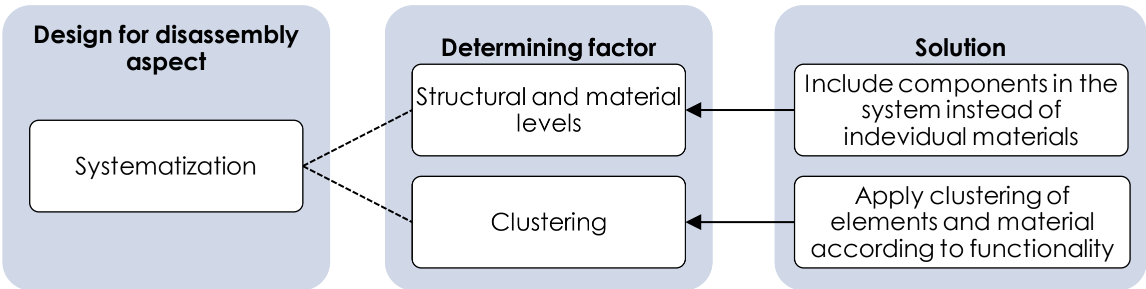


Figure 5-2 shows the martial levels that provide a facade built using precast concrete conventional panels with the required functionalities. It is clear that these materials and elements are separated in term of assembly. Every material or element is assembled separately which increases the assembly time at the building site and consequently complicates the disassembly processes.

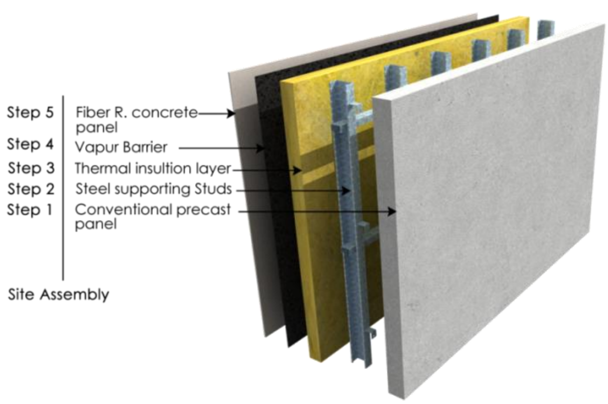


Figure 5-2: Material levels for precast conventional panels

.

To provide this facade system with more suitable aspects regarding assembly and disassembly and to raise its transformation capacity it is required to considered its material levels for systematization. This could be achieved by clustering of materials and elements according to their functionalities. In addition to gathering elements into components that are easy to be treated as a whole during the assembly and disassembly processes as figure 5-3 clarifies. The whole component is assembled off-site and brought as one unit to be installed at site.

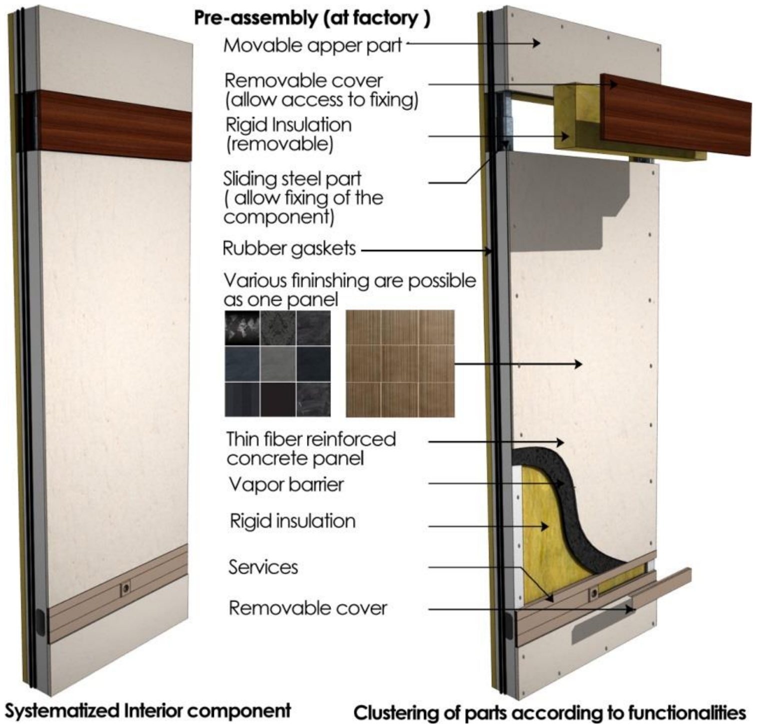
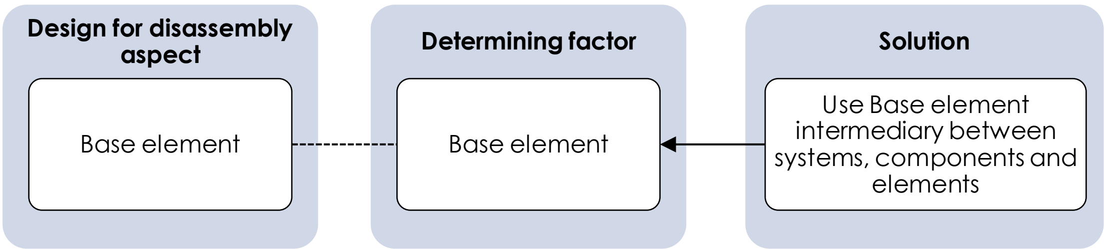


Figure 5-3: Clustering of elements and materials into one component

5.1.2 Base element

A base element is required to facilitate the gathering of items and systems. It also works as an intermediary device between items to help in simplifying the assembly and disassembly processes. The previous analysis of the precast concrete conventional panel system has shown that the current construction processes do not include the use of a base element. The following development demonstrates how the use of a base element will result in facilitating the gathering process of elements and systems.

Table 5-2: Development of base element specifications for conventional panel system



The following figures show the use of a concrete frame as a base element that gathers insulation material, vapor barrier and the wall services into one component. The concrete frame also helps in connecting together elements and components through the system. It is also possible to use a steel frame instead of the concrete frame, however, the concrete frame could be more suitable when fire resistant according to building code should be considered.

The use of the base element also provides an easy way to separate and demount the component into its elements and material levels. The disassembly of components to their material levels facilitates maintenance, modification and reuse. Consequently, it provides the component and the whole system with a higher environmental and economic value through and at the end-of-life of the system. The elements could be fixed to the base element using demountable connections, mainly steel bolts that support multiple assembly and disassembly processes.

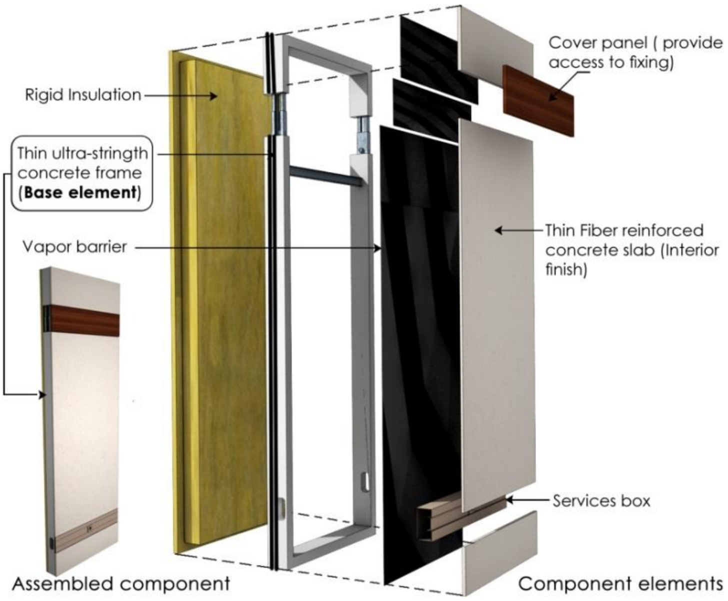


Figure 5-4: The use of concrete frame as a base element and its function as intermediary between elements and components

5.1.3 Assembly

The previous analysis also showed that some assembly aspects must be taken into consideration for the sake of higher disassembly potential of precast concrete conventional panels. The following section shows the suggested developments.

Table 5-3: Development of assembly aspects of conventional precast panels

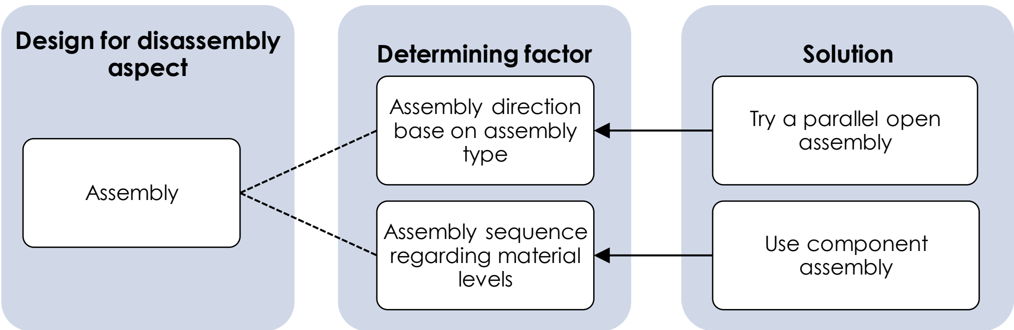


Figure 5-2 in the previous section shows the current status of constructing a precast concrete conventional panel façade. It also lists the steps of the assembly that occur on site. Figure 5-4 illustrates the development of the system in which pre-assembly processes took place in the factory. Such preassembly provides a complete preassembled component that can be assembled and disassembled in a parallel sequence on site as it is clarified in figure 5-5 below.

5.1.4 Geometry of element edge

In some cases the geometry of element edge shapes a hindrance to the ease of assembly and disassembly of elements and components. When the integral panel-to-panel joint is used the geometry of element edge restricts disassembly to one direction and a specific disassembly sequence. However the use of such method provides an environmental solution that prevents from rain water penetration, the high potential of disassembly requires open linear geometry. Such open geometry facilitates disassembly of the whole system or any of its parts through separation and independency of its elements. Instead the water proofing that the façades require could be provided through a variety of sealant types and jointing techniques.

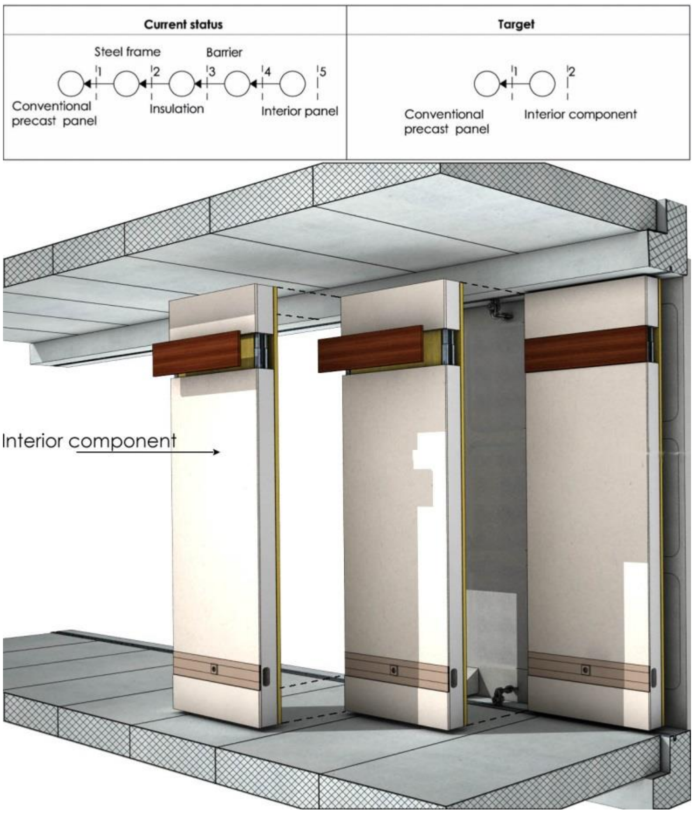


Figure 5-5: The use of components with conventional precast panels instead of separated materials and elements

Table 5-4: Development of geometry aspects of conventional precast panel system

Design for disassembly aspect	Determining factor	Solution
Geometry	Geometry of product/element edge	Use open linear geometry

Table 5-4 shows the DfD aspect that needs to be considered, the determining factor that needs to be developed and the proposed solution for geometry issues. The use of linear geometry of element edge is shown in figure 5-6. This technique is a normal practice in the construction of conventional panels and always accompanied with one of a variety of sealing and jointing techniques as previously mentioned in section 4.8.1.1.

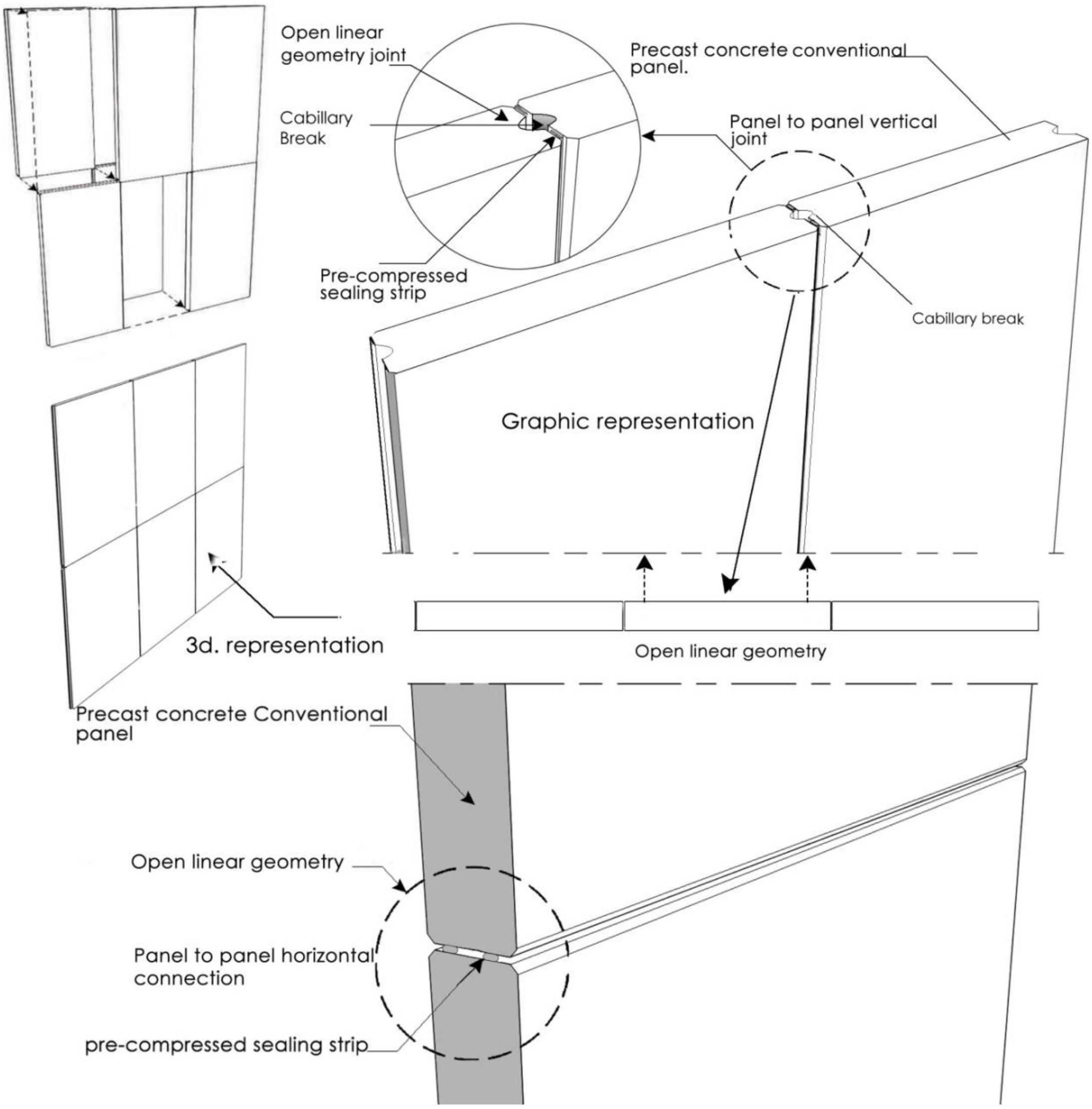


Figure 5-6: The use of open liner geometry in precast concrete conventional panels.

5.1.5 Connections

For the development of the system the following proposed table shows how reconsidering of some aspects could provide the system with higher disassembly potential. The major change aims to provide easy access to these connections to fasilitate their disassembly.

Table 5-5: Development of connection aspects

Design for disassembly aspect	Determining factor	Solution
Connections	Accessibility to fixing and intermediary	Provide accessibility to fixing
	Morphology of joint	Try knot (3d connection or point connection)

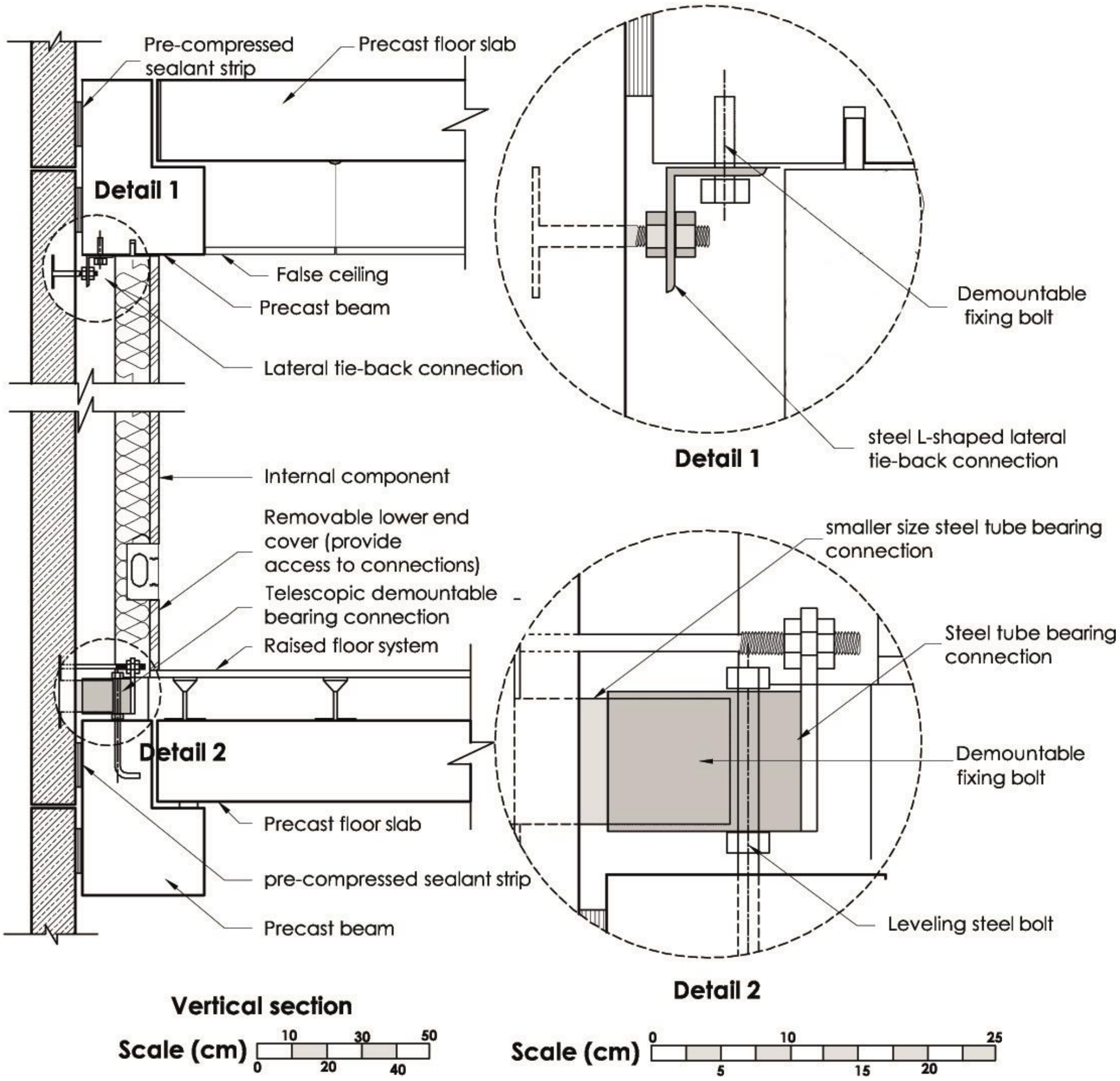


Figure 5-7: Development details for the bearing connection and lateral tie-back connection that connect conventional panels with load bearing structure.

Figure 5-7 and 5-8 show a developed bearing connection that provides high disassembly potential through telescopic steel tubes. Such device facilitates adjustability of the conventional panel distance from the load bearing frame and can be easily dismantled by demounting the fixing bolt. Figure 5-9 shows other ideas of development in case of the use of concrete consoles instead of steel. This idea includes the use of an integrated adjustable steel connection that simplifies the assembly and disassembly.

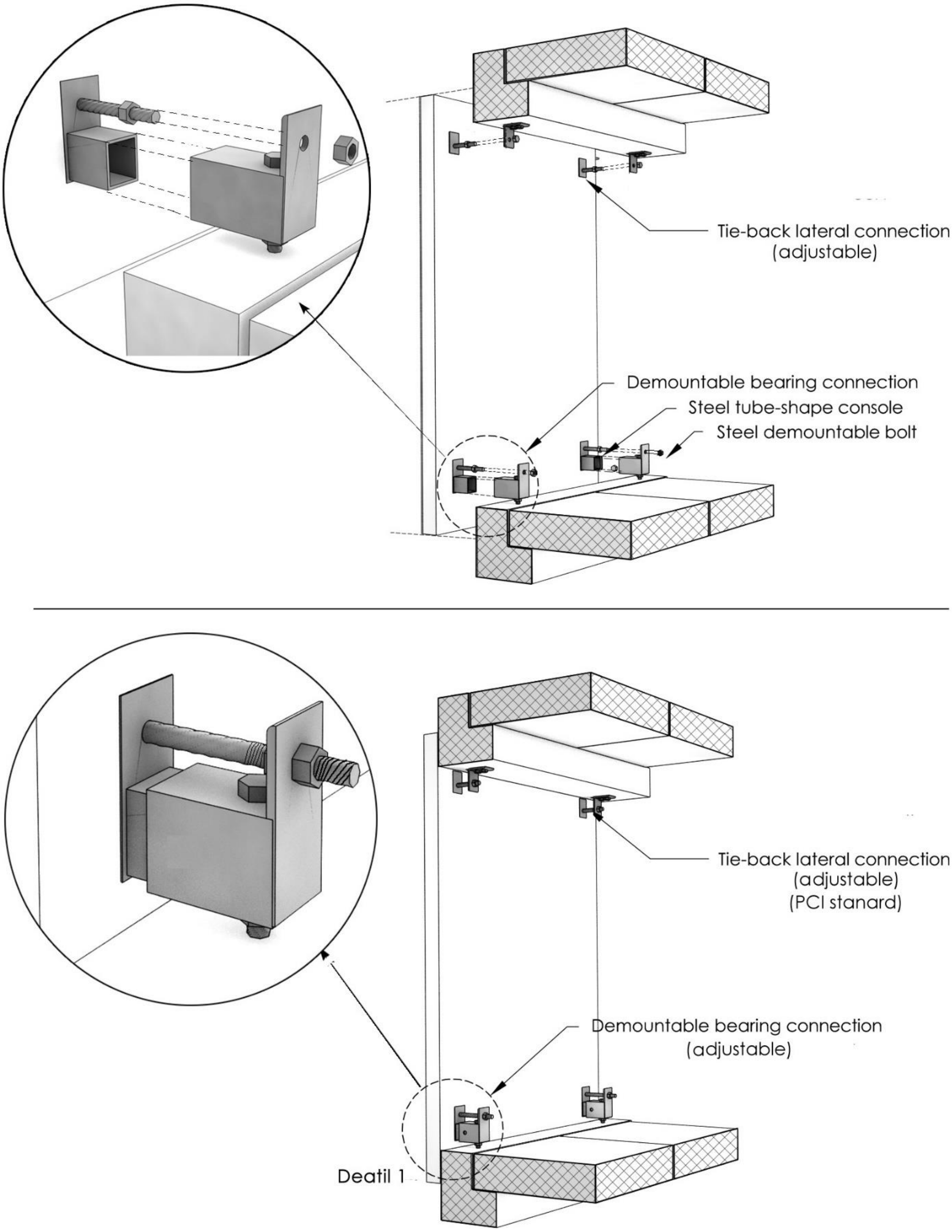


Figure 5-8: Three-dimensional details showing the development of demountable connections for conventional precast concrete panels.

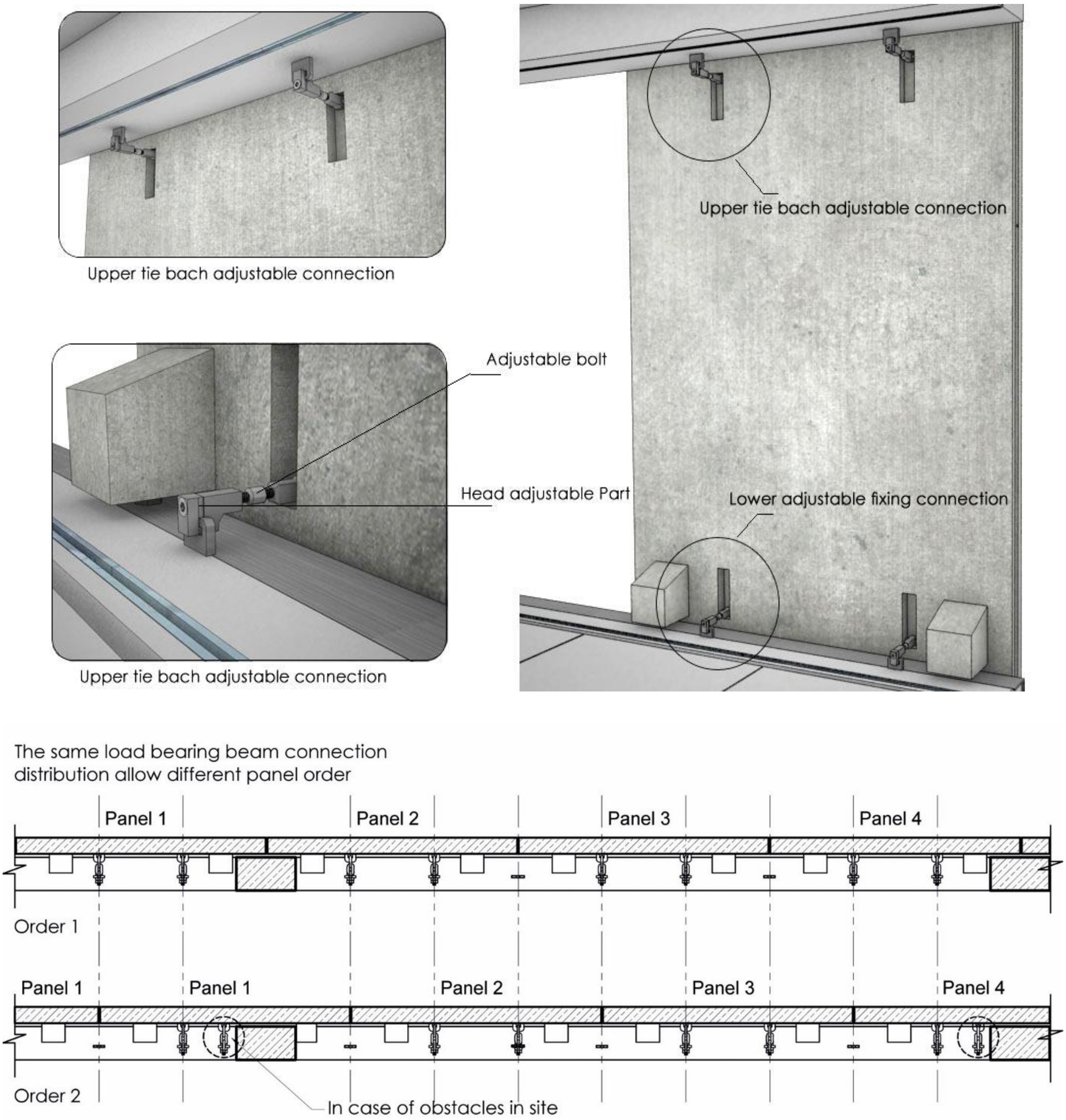


Figure 5-9: The use of adjustable fastener with the bearing consuls in precast concrete conventional panels

Figure 5-10 shows how the interior wall component of the conventional precast concrete panel wall system could be developed to have demountable connections. The concept is based on a sliding part at the upper part of the supporting frame. These sliding parts provide two advantages, on one hand they provide leveling for the interior panel to suite differences in the ceiling hight. And on the other hand they allow disassembly of the upper pin when the upper component level lowered down.

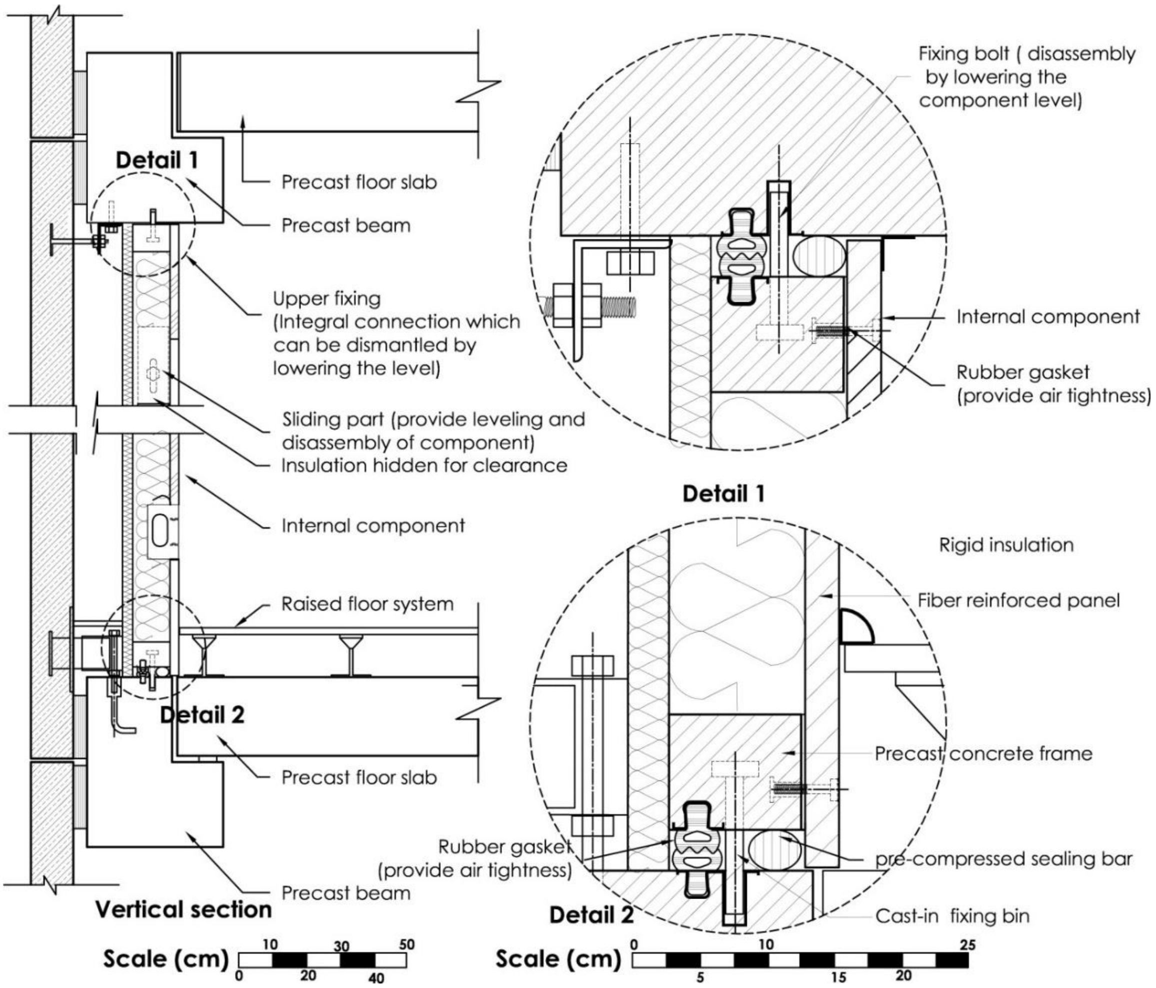
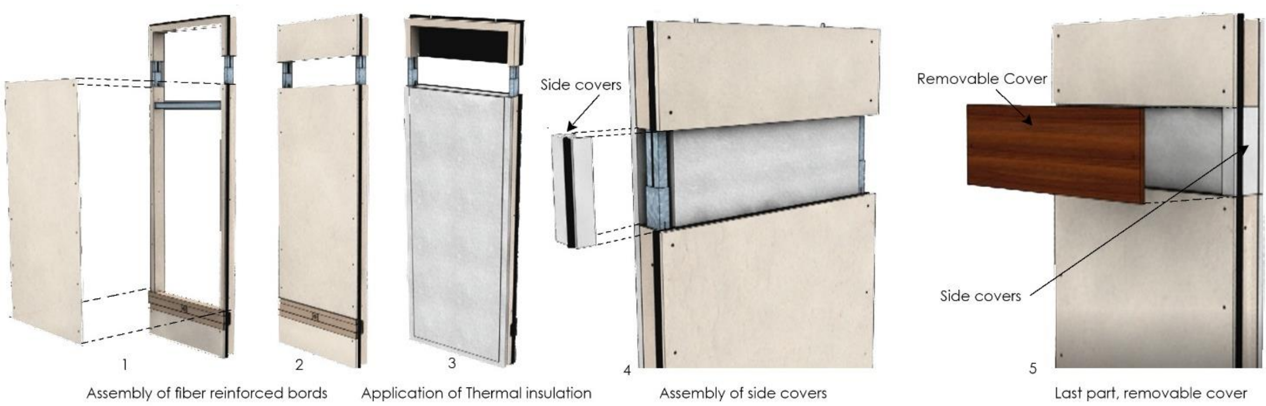


Figure 5-10: Development details for the demountable connection for the internal component of the conventional panel system.

Figure 5-11 shows how the interior component can be fixed to the load bearing beams by utilizeing two continuous grooves at the upper and lower beams. The grooves allow the panel to move along the beam axis which provides more flexibility of panels position. After positioning the panel, the upper part is raised till a sufficient friction and integration with the sealing rubber gaskets is developed. Then the demountable bolts are fixed. After that two side covers are added for completing the frame and sealing the edges. After that the upper insulation part is inserted from the side and a removable cover is added to close the component. The next step includes adding the following interior components.



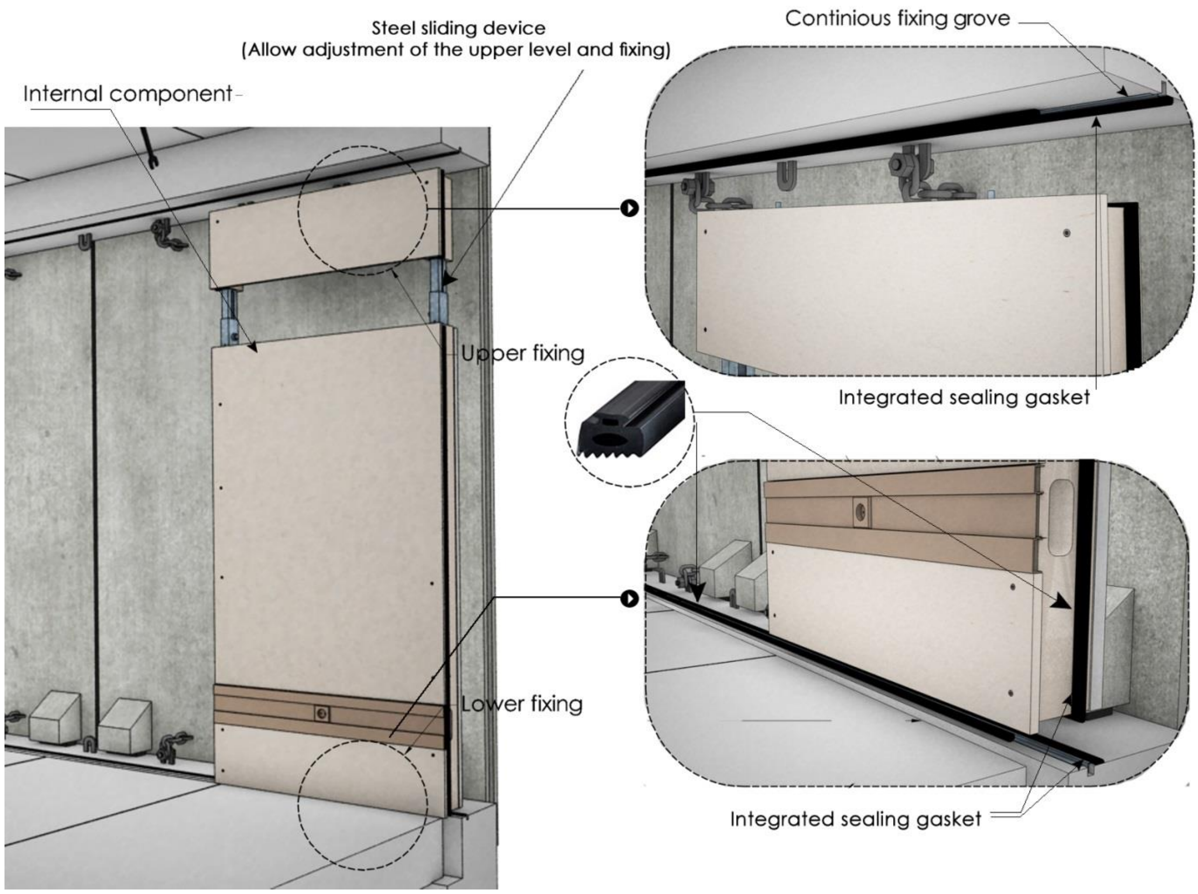


Figure 5-11: Three-dimensional model showing assembly of the interior part and development details for the demountable connection for the internal component of the conventional panel system.

Unlike the currently used system the removable upper cover of this developed system provides access to the connections of the interior panel which allows disassembly processes without any loss of material.

5.1.6 Results

The previous development concepts that have been applied to the conventional precast panel for providing high transformation capacity have led to a system with very high disassembly potential. Such system is not only supposed to facilitate reuse of materials and components - with very little or no material loss - but also facilitates and speeds up the assembly and disassembly processes and provide the ability to upgrade the insulation material and services. The following figure shows the evaluation of the developed system.

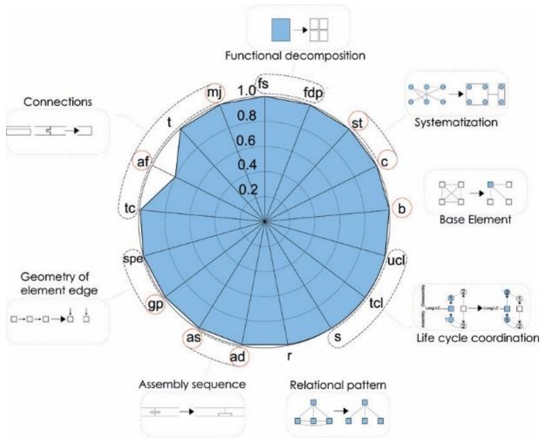


Figure 5-12: Evaluation chart showing the high transformation capacity through the development of the system

5.2 Development of the precast concrete sandwich panel system

The analysis that has been conducted on the previous parts has shown that precast sandwich panel system has achieved a high disassembly potential. Figure 5-13 indicates that some DfD determining factors have not achieved the required value. This means that with regard to this specific aspect the system will not perform well and some kind of material or time loss may occur during assembly and disassembly process. The determining factors that have achieved low values are:

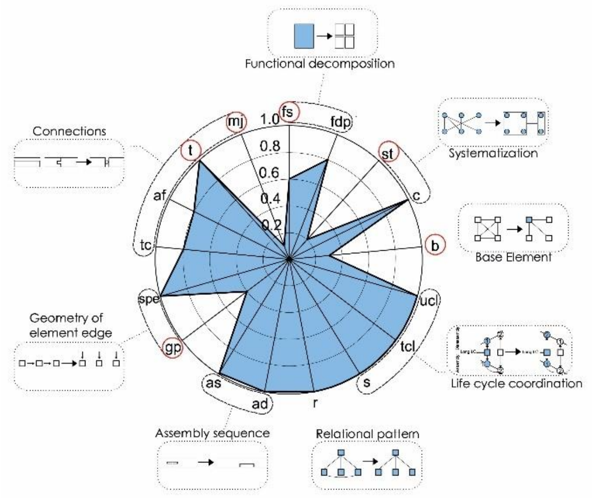


Figure 5-13: Precast sandwich panel evaluation chart showing areas of limited transformation capacity

- systematization regarding structural and material levels
- base element specification
- geometry of element edge (for some kind of sandwich panels) and
- morphology of joint.

The following development is going to take into consideration the above-mentioned factors to provide the system with a higher transformation capacity that will result in a less environmental impact.

5.2.1 Development of functional decomposition aspect

The system has shown average score regarding functional separation at the elements level since the integration of functions into one element has been applied. Such integration complicates the disassembly of material levels of this system and restricts it to a specific disassembly sequence.

Table 5-6: Area that needs further developments in the DfD aspects of precast concrete sandwich panels and the proposed solution for functional decomposition

Design for disassembly aspect	Determining factor	Solution
Functional decomposition	Functional separation	Try to seperate functions

Figure 5-14 demonstrates how different functions and materials have been integrated into one element. The insulation, the appearance and the bearing elements are gathered into one interpenetrating entity that cannot be disassembled.

However, these features have a very convergent life cycle but high transformation capacity requires separation of functions. The architectural appearance in this case has a specialty where the adaptability may require change of the finishing due to an expected fashion obsolescence through time. Figure 5-15 shows a development concept regarding relations between functions. The current design of precast sandwich panels as shown to the left includes interpenetrating of all wall functions into one monolithic entity.

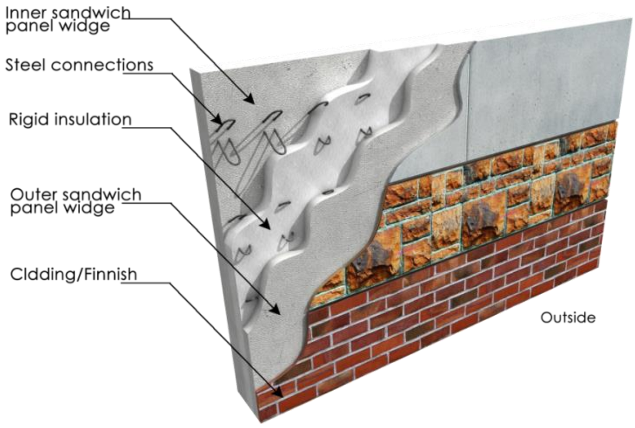


Figure 5-14: Technical composition of the precast sandwich panels shows the relation between materials and functions.

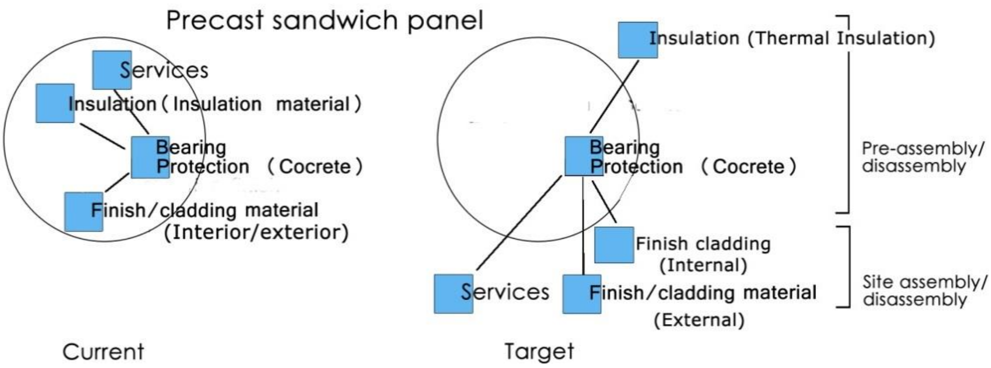


Figure 5-15: Relation of functions through the precast sandwich panel system to the left the current situation to the right the target

The figure above demonstrates in the target how features that have higher exchangeability rate such as the services could be separated. The development also includes separation of insulation where the sandwich panel could be disassembled either for replacement of thermal insulation material or the reuse or recycle of its parts. The application of the development concepts of functional separation for sandwich panels are illustrated in following figures. These figures show how different functions could be separated through the use of demountable connections.

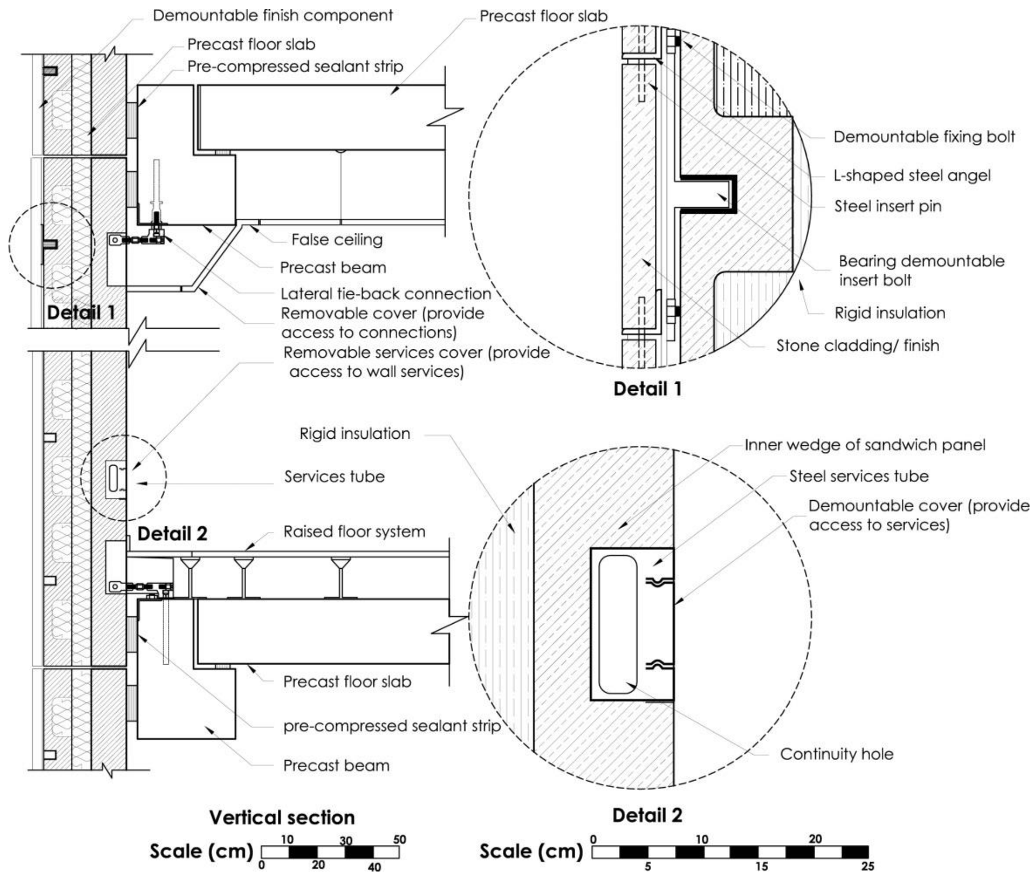


Figure 5-16: Vertical section in a sandwich panel façade system

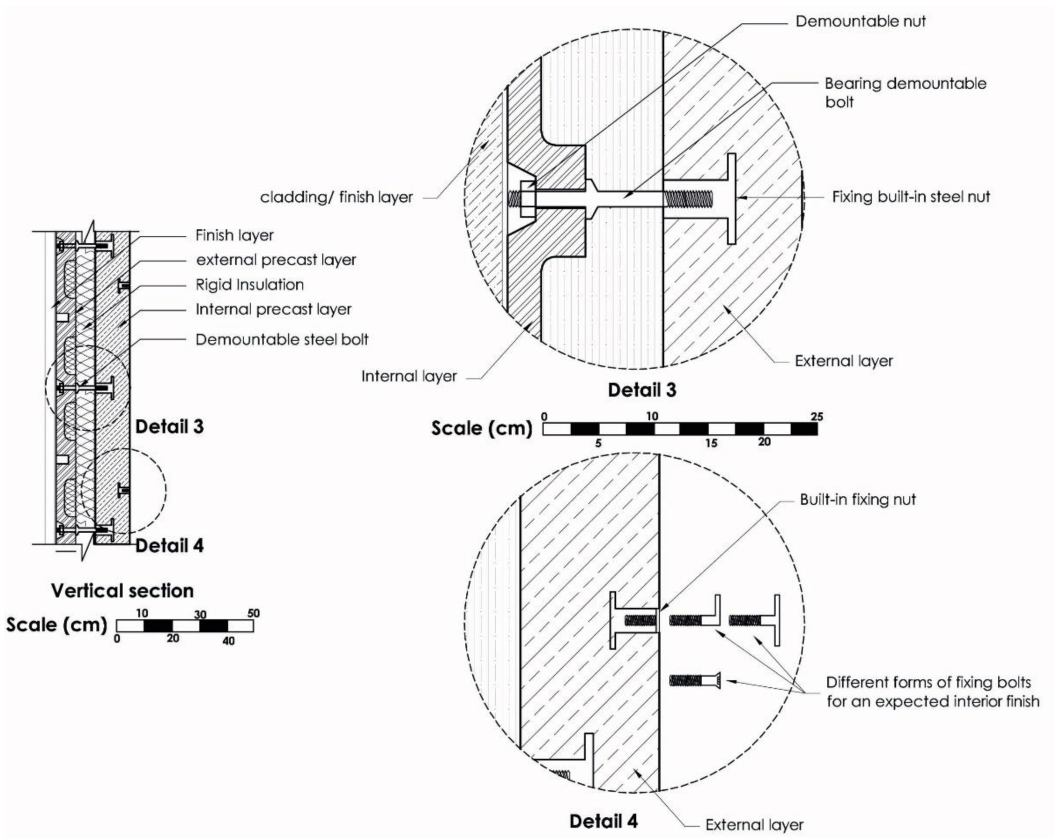


Figure 5-17: Vertical section in a sandwich panel system

Detail 1 in figure 5-16 shows separation of the cladding system as demountable components and detail 2 shows separation of services. Detail 3 in figure 5-17 shows separation of the external and internal layers through a demountable bolt which can be replaced. A longer bolt could be used to increase the thickness of insulation material when required. Detail 4 shows separation of an expected internal cladding system as demountable components through a demountable bolt.

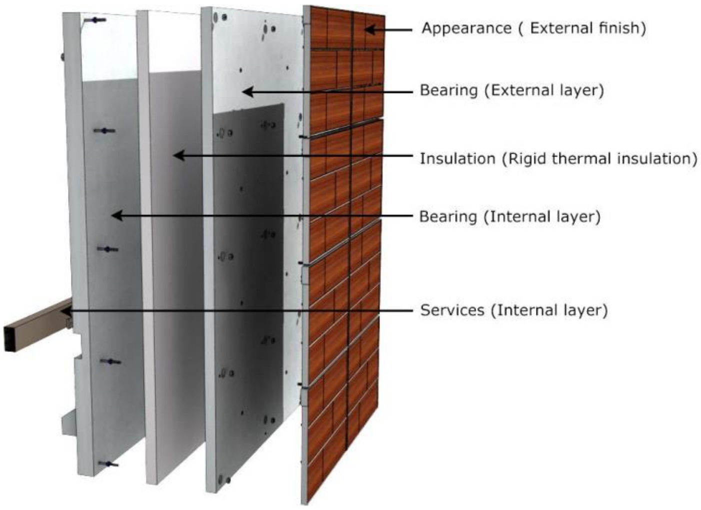


Figure 5-18: The proposed separation of functions in sandwich panels

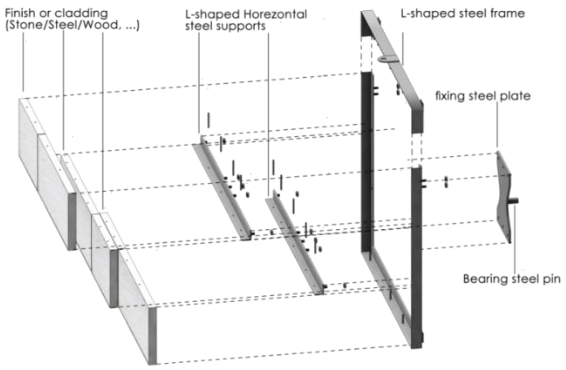


Figure 5-19: Parts of the demountable finish component that provide the appearance to the sandwich panel façade and could be dismantled for replacement or reuse of its parts.

Figure 5-19 shows the assembly parts of a demountable finishing component. The finish materials for this component may contain: natural stone, steel sheets, wood or any other finish material. In addition to that a support bearing system consisted of L- shaped frame and two horizontal L-shaped elements that support the finish material and connected to a steel plate is used. The steel plate contains a bearing pin; this pin is inserted into a cylindrical steel tube cast-in connection in the external wedge of the sandwich panel (see appendix 17 for more details and connection ideas).

Figure 5-20: Different finish material that can be used in the exterior finish component of the sandwich panel

Figure 5-21 and figure 5-22 show a three-dimensional presentation of the proposed development for the sandwich panel facades. The figures illustrate the separation of the finish as an important step to adaptability and reuse of materials and components.

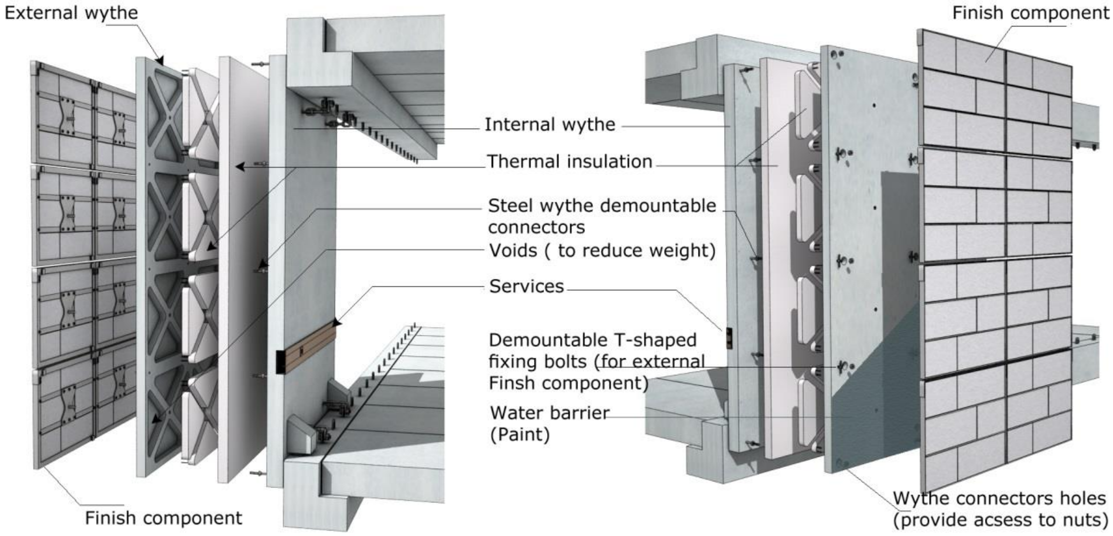


Figure 5-21: Assembly parts of the sandwich panel and the finish component

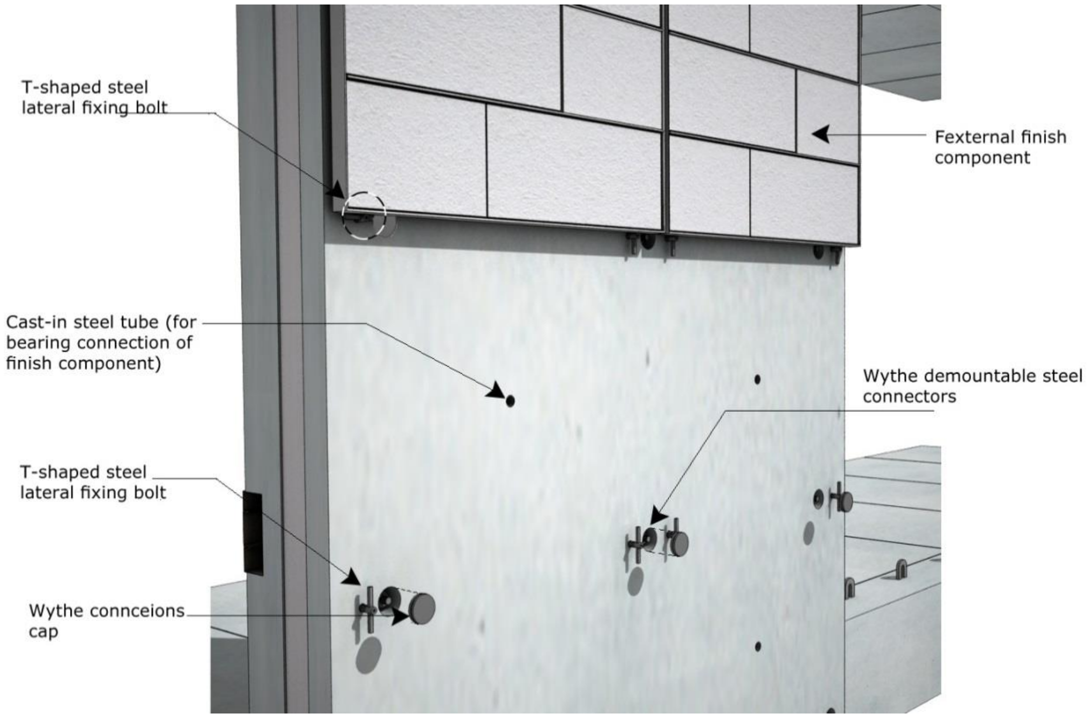


Figure 5-22: Fixing of the finish component by the T-shaped pins.

5.2.2 Development of the systematization aspects

The sandwich panel system has shown very low score with regard to structural and material levels. Such low score could be attributed to the existed interpenetrating of functions and materials into one element. The interpenetrating complicates the disassembly of material and structural levels and prevent from obtaining these materials in a good manner for reuse.

Table 5-7: Area that needs further developments in the DfD aspects of precast concrete sandwich panels and the proposed solution for systematization

Design for disassembly aspect	Determining factor	Solution
Systematization	Structural and material levels	Use components

The structural and material level is one of two aspects that determine how systematized the system is. The proposed development includes emancipation of the structural and material level by using components instead of monolithic entities. These components simplify the assembly and disassembly processes of systems and facilitate the reach to their material level. In the case of sandwich panel's facades systematization have been applied to the external side by including finishing component that facilitates the disassembly and reuse of the finishing material. Also, the interior part has been supplied by a services component that facilitates replacement and addition of new services without compromising the sandwich panel to damage (see figure 5-23).

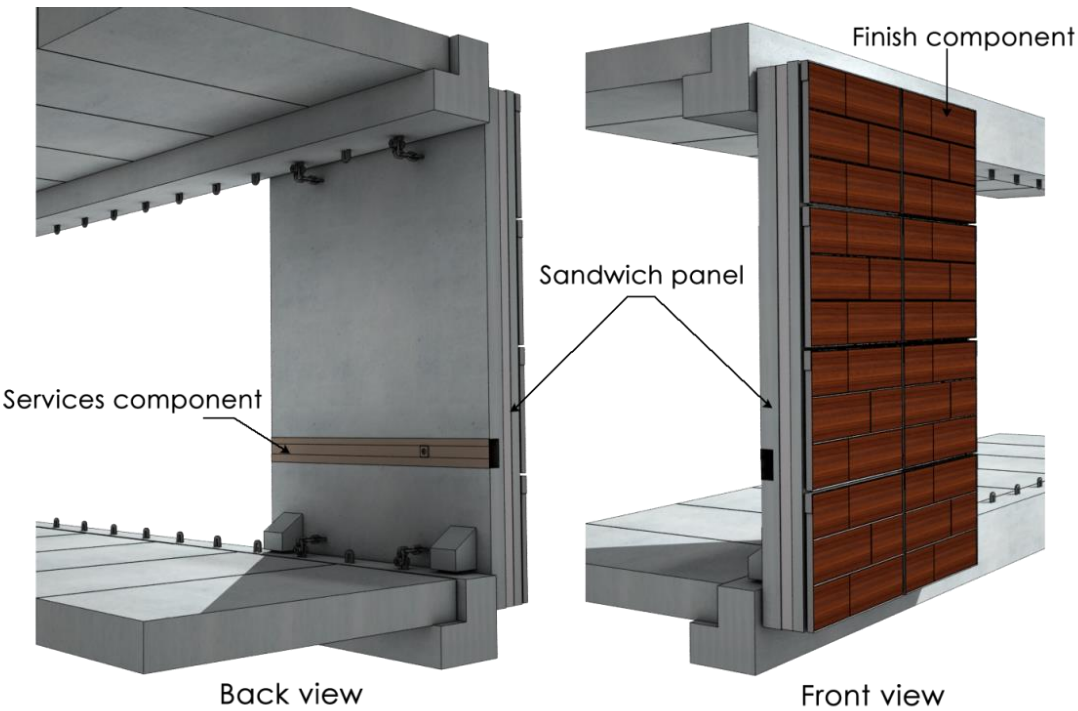
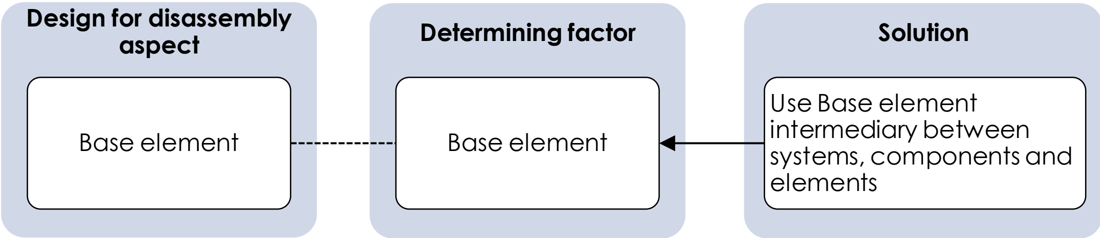


Figure 5-23: The use of components in sandwich panels

5.2.3 Base element

A base element facilitates the assembly and disassembly processes through gathering different components and parts together. The previous analysis of precast concrete sandwich panel system has shown that the currently used system does not include the utilization of a base element. All functions and materials in the system are combined as a one interpenetrating entity.

Table 5-8: Area that needs further developments in the DfD aspects of precast concrete conventional panels and the proposed solution for base element specifications



The following development shown in figure 5-24 indicates that the interior layer of the sandwich panel itself has been used as a base element. This base element gathers the appearance and services functions of the system and facilitate their assembly and disassembly. The sandwich panels also work - in addition to its function of protection - as an intermediate that supports the system and transfers its loads to the load bearing system.

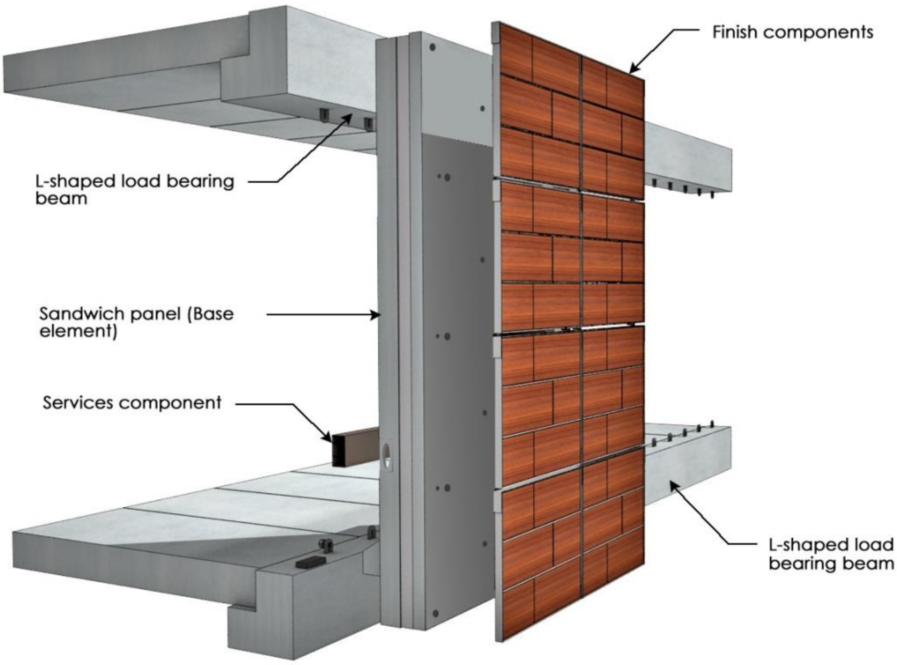
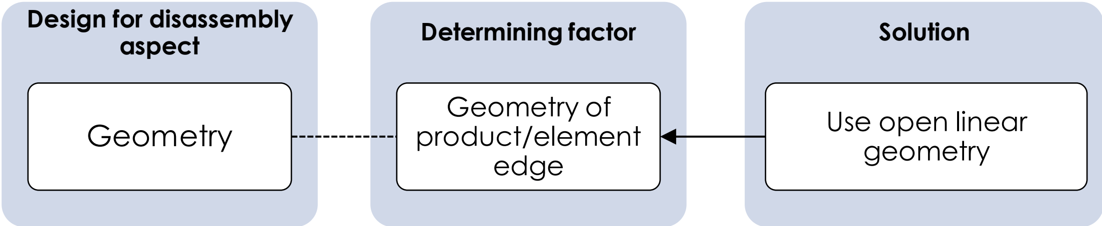


Figure 5-24: The sandwich panel as base element

5.2.4 Geometry of element edge

For more protection from water penetration a specific design for the edges of the element is applied in some cases. Drained joint panel to panel connection which has been previously discussed is one example of such specific design. This type of geometry of element edge shapes a hindrance to the ease of assembly and disassembly of the panels. So it is recommended to use the open linear geometry of element edge for high disassembly potential. Open linear geometry will facilitate disassembly of the whole system or any of its parts through separation and independence of functions and materials. The following details in figure 5-25 show how the required air tightness and protection from water could be achived through pre-compressed airtightness strips and elastic sealants. Such technique has already been used for concrete façade panels.

Table 5-9: Area that needs further developments in the DfD aspects of precast concrete sandwich panels (the drained joint case) and the proposed solution for Geometry of element edge



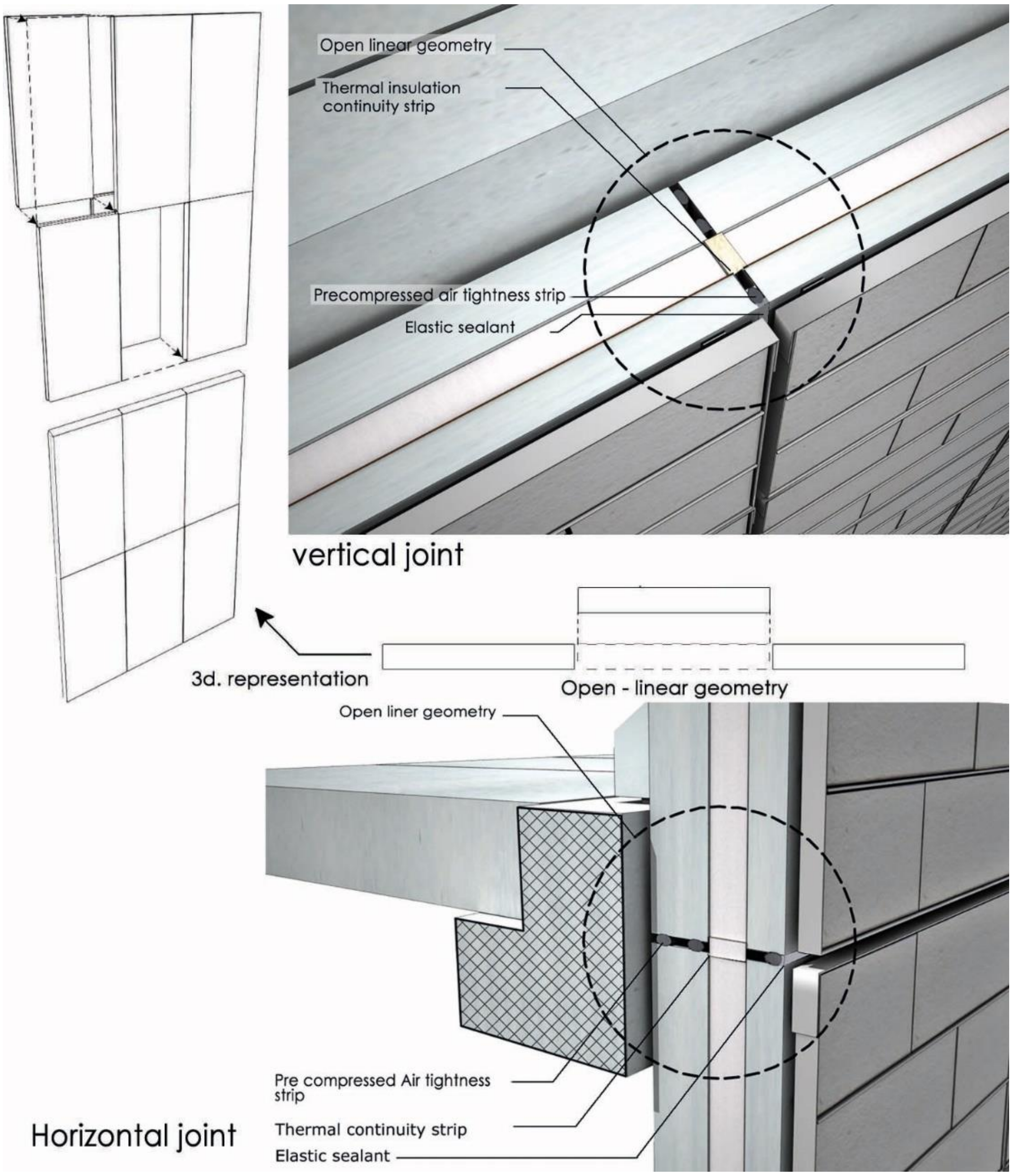
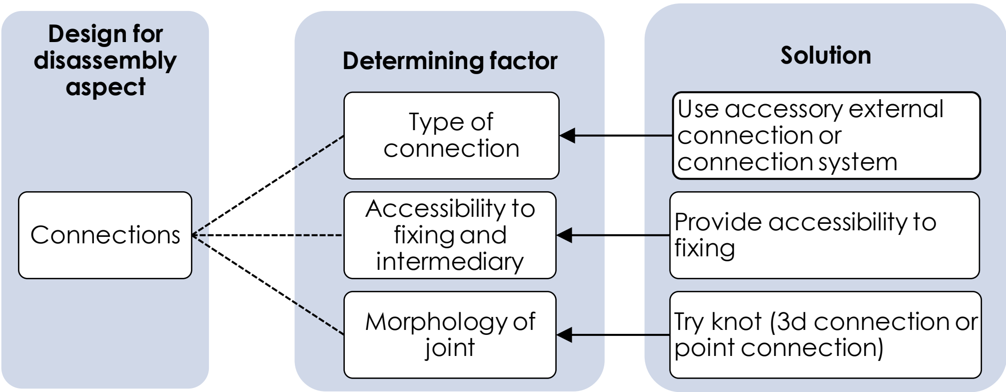


Figure 5-25: Open linear geometry of element edge for sandwich panels

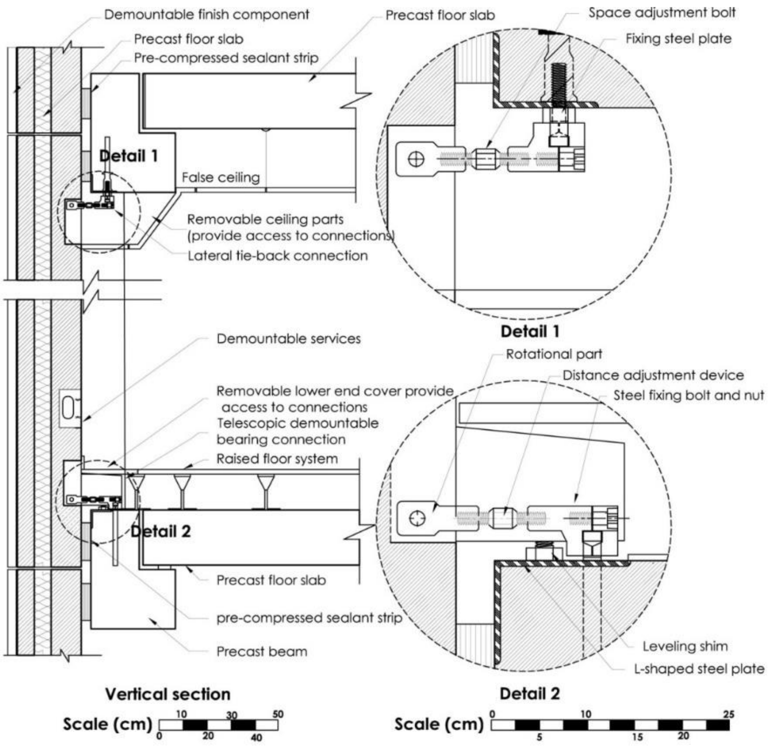
5.2.5 Connections

The same concepts of connections that have been used in the previous conventional panel system could be used for sandwich panels. This concept will provide the system with high disassembly potential. In this case the following aspects will be deveeloped.

Table 5-10: Area that needs further developments in the DfD aspects of precast concrete sandwich panels and the proposed solution for connections



The Use of accessory external connection which is represented by steel plates and adjustable fixing connection as shown in figure 5-26 provides the system with high disassembly potential. This advantage is obtained by converting demountable connection into easily assemble and disassemble demountable connections. Accessibility to fixing has been solved by the use of removable parts in the floor and ceiling systems. The use of adjustable connection for fixing purposes provides a solution for the morphology of joint through flexibility and adaptation. This connection works as a three-dimensional connection that accommodates different directions in addition to its length that can be reduced or increased.



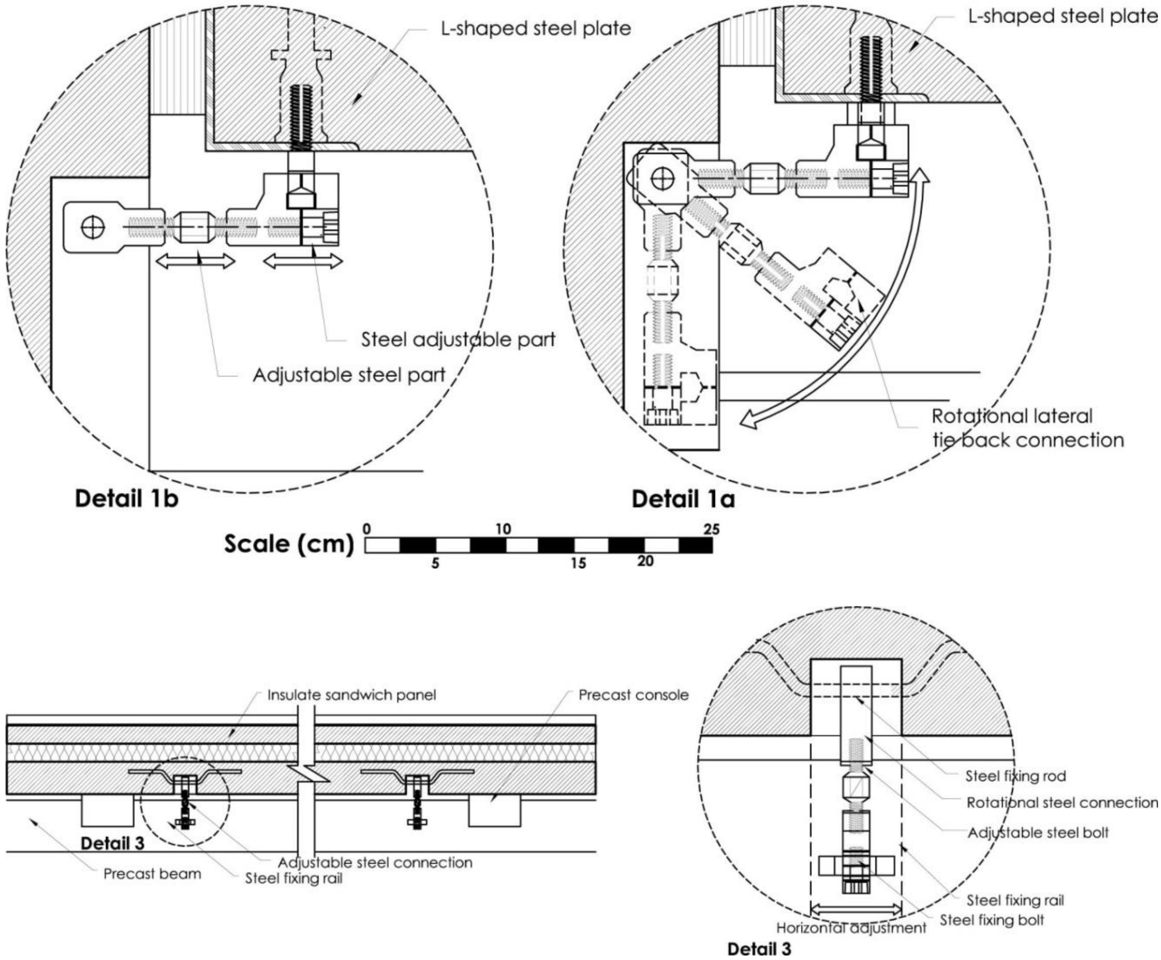


Figure 5-26: Connection development for sandwich panel façade system

5.2.6 Results

Figure 5-27 shows the evaluation chart for the developed precast sandwich panel system which has been designed for high transformation capacity. Through the consideration of the weak DfD aspects in the currently used system, the newly developed facilitates reuse of materials and components with very little or no material loss. In addition to that the applied developments simplify the assembly and disassembly processes as well as speed up the construction. The following figure shows the evaluation of the developed system.

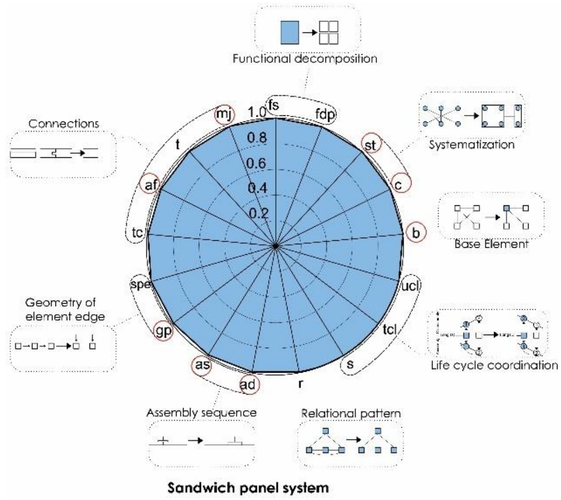


Figure 5-27: Evaluation chart showing the high transformation capacity through the development of the system

However, the previous analysis and evaluation of the precast sandwich panel system has shown high disassembly potential, there was a chance for advanced developments. Regarding systematization, base element, assembly sequence, the geometry of element edge, accessibility to fixing and morphology of joint there was a chance to improve the performance of these aspects. The previous development concepts have led to a very high disassembly potential for this system. (See appendix 18 for value proposition for the various façade systems)

5.3 The architectural design of the precast panels

The architectural design of the building façades is one of the crucial aspects to the success of any project. However, the standard shapes of the precast panels provide a higher potential for reuse, the opportunity to design various panels forms that enrich the architectural distinction is not limited. It can be concluded that the design considerations for precast demountable facades should be directed to their transformation capacity as well as the reuse potential of the system and its parts.

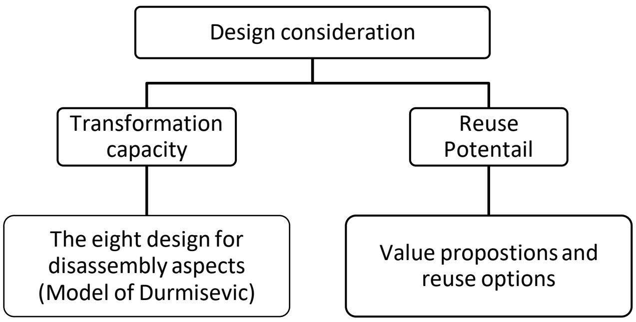


Figure 5-28: Design consideration for demountable precast concrete facades

5.4 Modeling and application

In this section, modeling and application of the developed concepts of facades systems will be applied to the current design of an existing building. The faculty of architecture and landscape building, Leibniz University Hanover, was chosen as a case study. The high rate of standardization from one side and the existence of variety of façade types from the other side makes it a suitable choice. The building of the faculty of Architecture and landscape was constructed using cast-in-situ loadbearing concrete frame system, solid slabs and shear walls. Precast concrete cladding panels have been applied to the majority of the exterior facades.

5.4.1 Analysis of the current façade design

In this section the existing original drawings including plans, sections and photos will be used for the analysis that shows the current façade systems. The building consists of four parts with various façade designs regarding structural aspects. Figure 5-29 shows the current building (see appendix 19 for details).

Figure 5-29: External shoots show the different heights of the building parts (Google maps, 2017)

Figure 5-30: The use of cast in situ concrete with cladding panels in the facades

Figure 5-31: The use of aluminum curtain walls in the facades

The current facades of the faculty buildings could be classified into two types:

- cast-in-situ concrete facades with precast cladding panels and
- aluminum curtain walls.

To obtain a more precise evaluation of the first type, the facades is going to be evaluated in two parts. The first part represents the cladding panels and the window systems and the second part represents the inner cast-in-situ concrete part. Figure 5-32 shows that part one has higher disassembly potential than part two, however, an assessment of the façade will be performed. Taking into consideration the relation between the two parts, the knowledge model of Durmisevic will be utilized to show the response of the system. Every determining factor of the DfD aspects of both parts will be evaluated. Figure 5-33 shows a typical connection detail that is used to connect precast cladding panels to cast-in-situ walls. Such details will help in determining the connection aspects.

5.4.2 Assessment of the current facades systems

Figure 5-34 and 5-34 show the evaluation of the existing façade system and the proposed façade system. A wider analysis process with figures will be dedicated to the new proposed systems due to the higher level of complexity compared to the current conventional façade system.

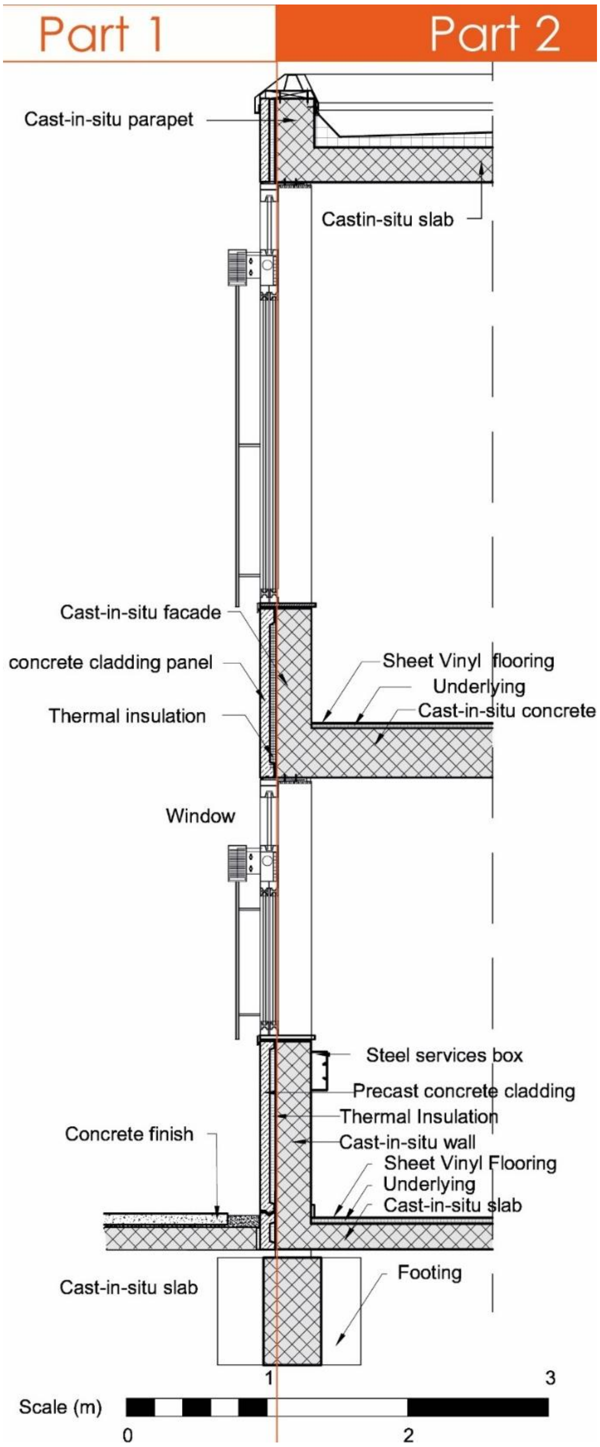


Figure 5-32: Vertical section show the construction system of “building one” façade.

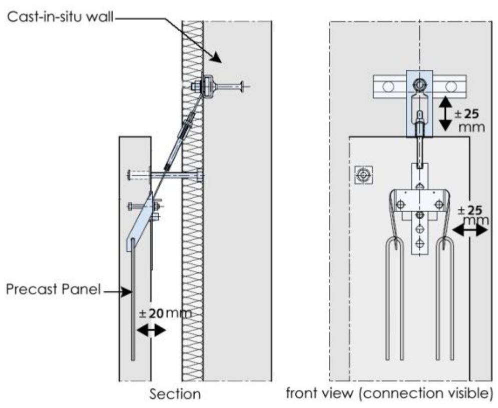


Figure 5-33: Typical connection detail of precast cladding panels (Duplex, n.d.)

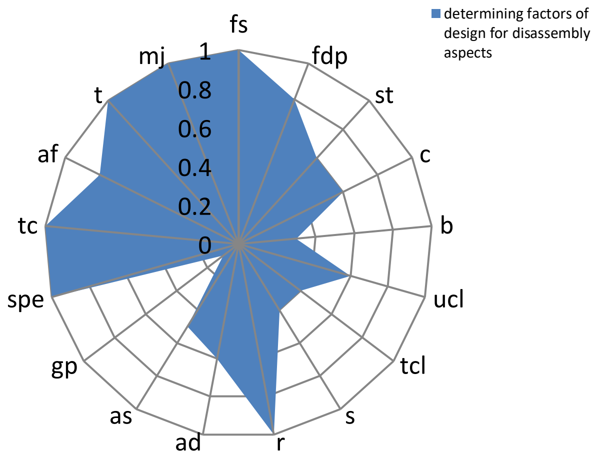


Figure 5-34: Evaluation chart of part 1 of the façade system

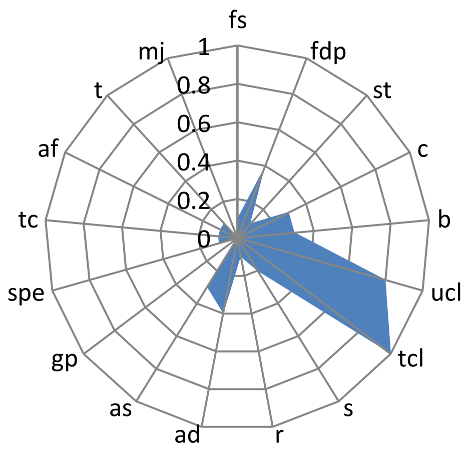


Figure 5-35: Evaluation chart of part 2 of the façade system

The evaluation shows that part one of the façade system which is consisted of the external cladding of the façades has a medium disassembly potential. Part two which is consisted of cast-in-situ concrete has low disassembly potential where most of the determining factors of the DfD aspects showed very little response. That could be attributed mainly to the traditional construction methods of cast-in-situ concrete which do not take these aspects into consideration. The reuse potential of the faced system will be limited to the cladding panels and the Aluminum windows. The insulation material could be recycled after a quality test applied, but the cast-in-situ parts has no option except demolition.

5.4.2.1 The new sustainable proposal

The current facades system of the faculty buildings will be replaced with a new proposed demountable system that provide high disassembly potential and transformation capacity. In the last chapter some concepts have been introduced for the development of existing precast systems to make them more sustainable and responsive to transformation capacity. In this part these developed systems will be utilized to show their ability for providing a complete sustainable façade system that takes the life cycle design into consideration.

5.4.2.2 Analysis and evaluation of the proposed demountable façades systems

To provide a clear understanding of the new proposed façades an analysis of the disassembly potential will be performed. As previously mentioned, the typology of configuration decides the level of disassembly in any system. The following figures analyze the independence and exchangeability of the façade system and its parts through material levels, technical composition and physical integration.

- **Material levels**

The new proposed façade system provides emancipation of all material levels including the exterior and interior parts through demountable connections. A suitable level of independence and exchangeability have been provided to allow change and reuse parts and materials.

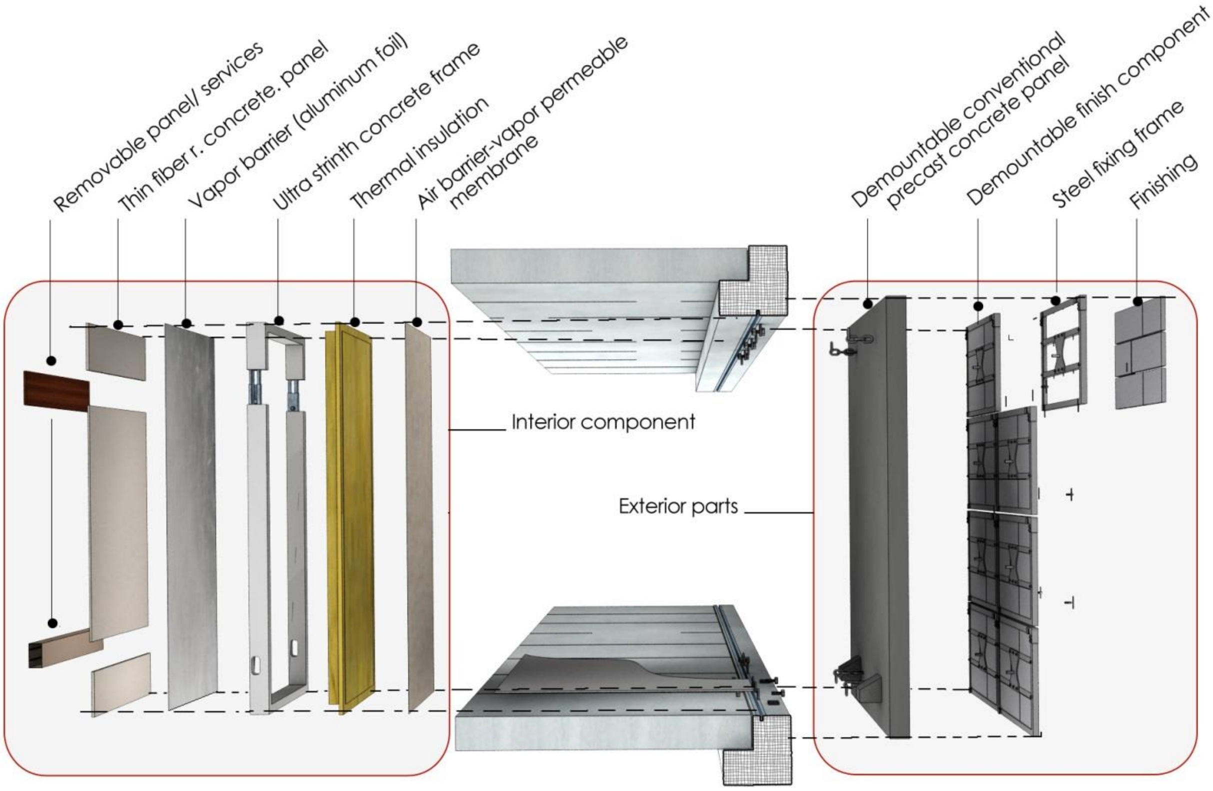


Figure 5-36: The material levels of the proposed façade system

- **Technical composition**

The following figure shows the hierarchal arrangements and the relation between materials and functions which identify the technical composition of the façade system.

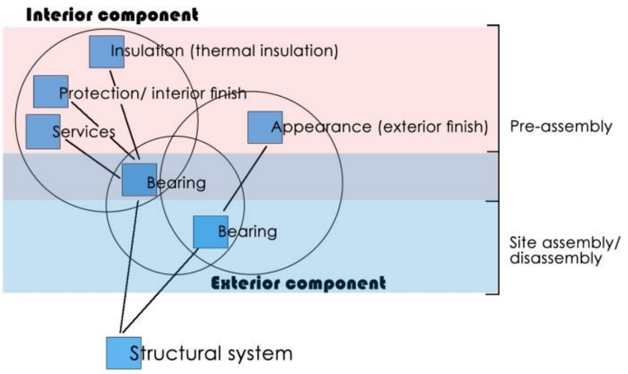


Figure 5-37: The functional dependence of the proposed facades

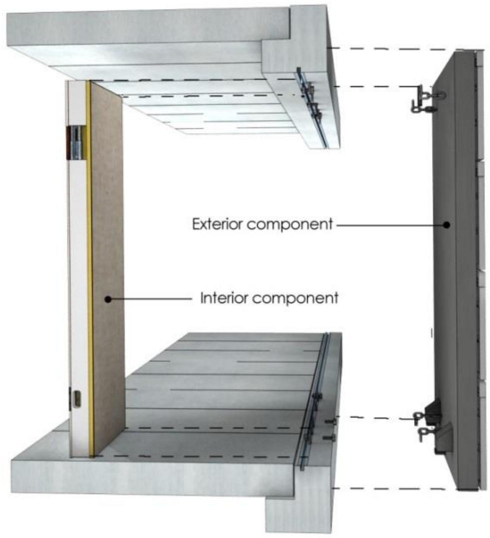


Figure 5-38: The technical composition of the demountable proposed facades

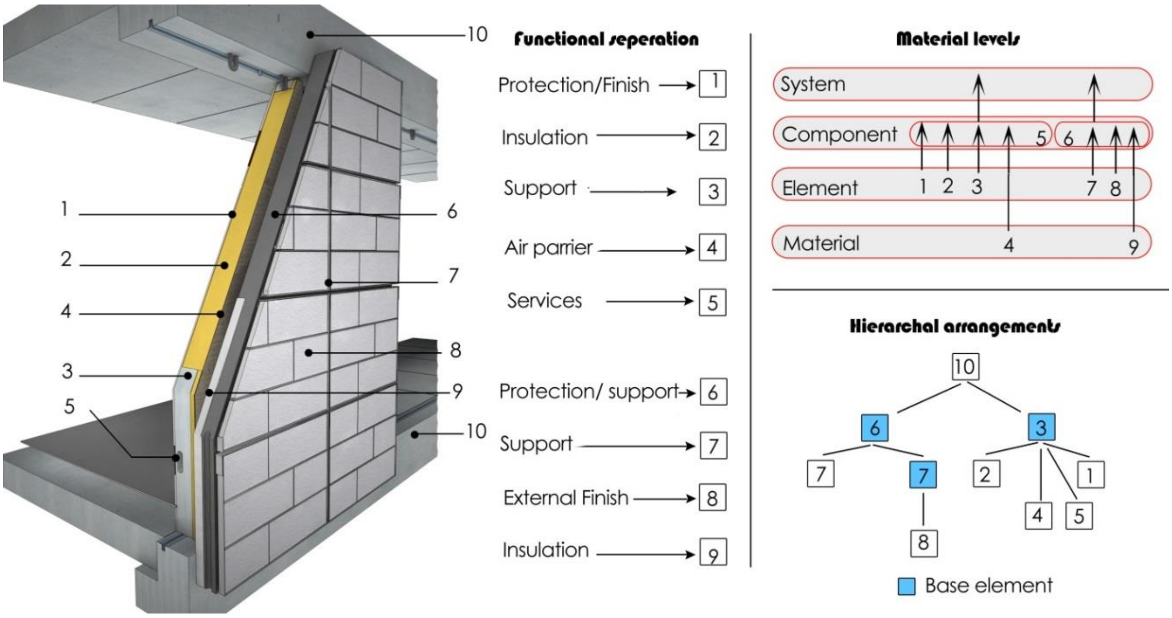


Figure 5-39: Analysis of the functional decomposition, systematization and relational patterns

- **Physical integration**

The type of connection, the geometry of element edge and the assembly sequence decide the independence and exchangeability of the physical integration of any system. The following analysis shows the response of the proposed façade system to these aspects.

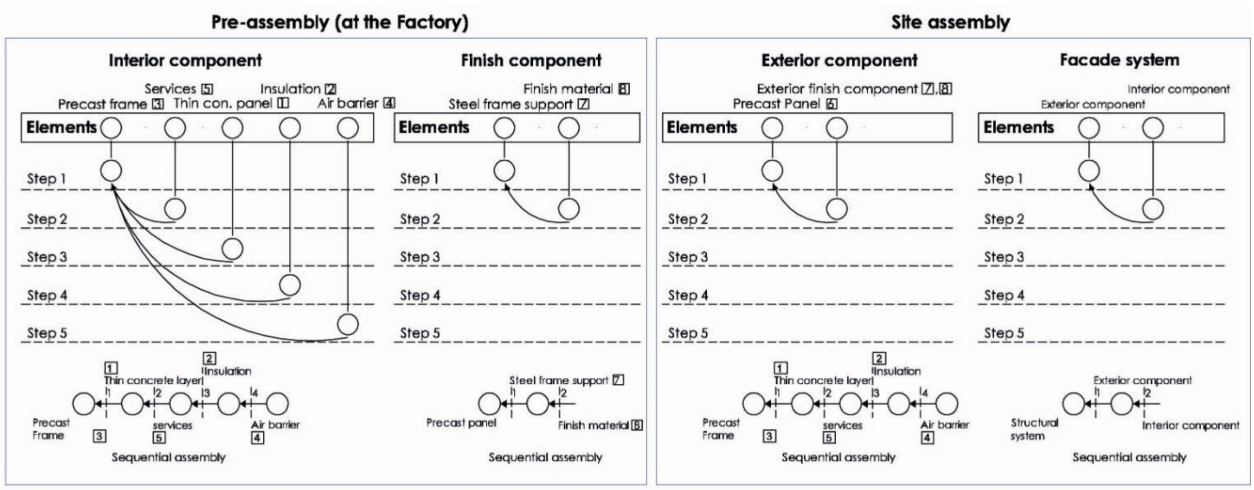


Figure 5-40: Assembly of the precast concrete façade system and its component

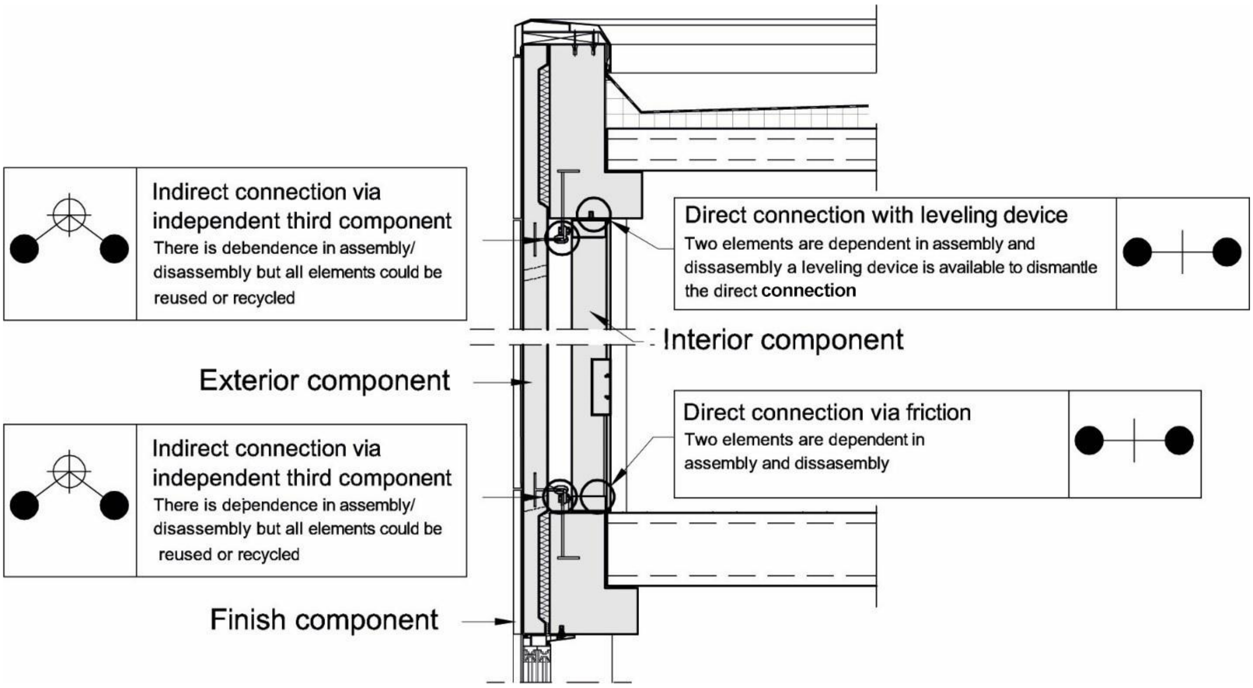
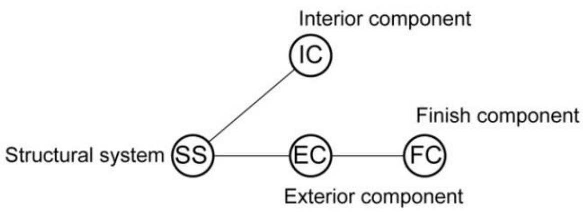


Figure 5-41: Connection types of the proposed demountable facades



Connection	Accessibility	Tolerance	Morphology of joint
SS-IC	Accessible	high tolerance	point connection
SS-EC	Accessible	high tolerance	Knot (3d)connection
EC-FC	Accessible	high tolerance	point connection

Geometry of joints

Joint	Geometry
SS-IC	Integral (Open when connection dismantled)
SS-EC	Open (linear)
EC-FC	Open (linear)

Figure 5-42: Aspects of connections and geometry of the proposed façade system

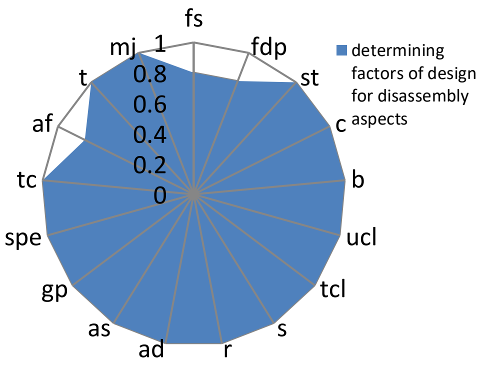


Figure 5-43: Evaluation chart of the external component of the façade the new proposed system

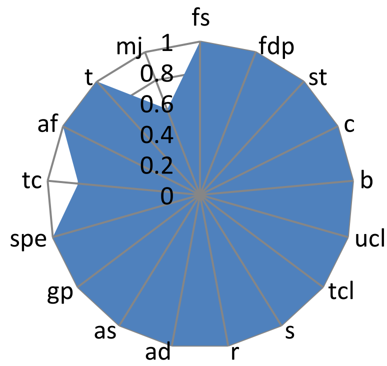


Figure 5-44: Evaluation chart of the interior component of the proposed façade system

The evaluation indicates that both parts of the proposed façade system have achieved high disassembly and reuse potential. Compared to the current façade system, the new proposed one will not only provide disassembly potential of all parts and prevent from material loss but also provide high reuse potential.

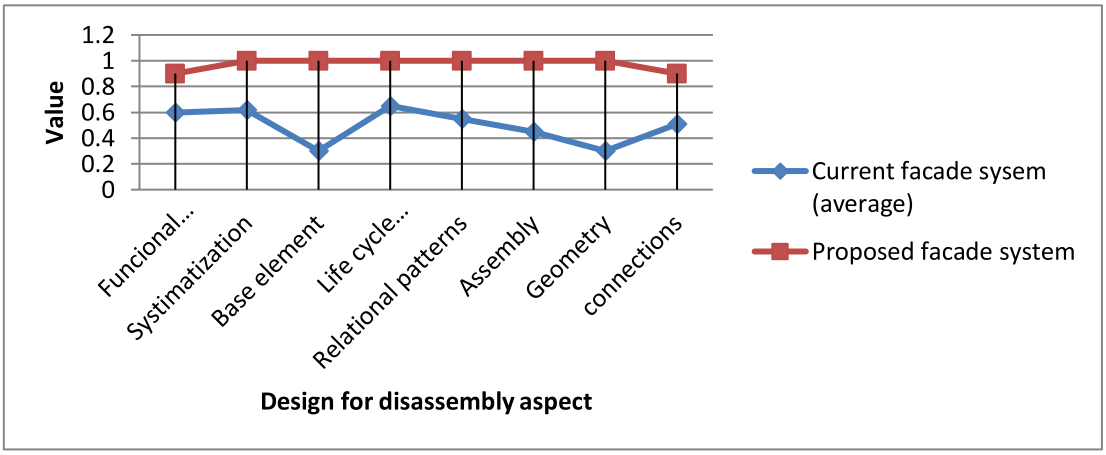


Figure 5-45: Output of the forth level of the evaluation model

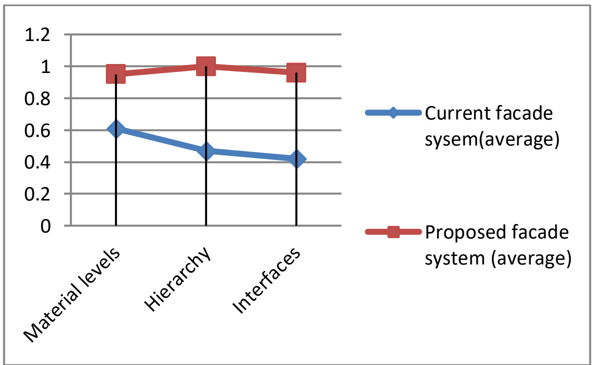


Figure 5-46: Output of the third level of the evaluation model

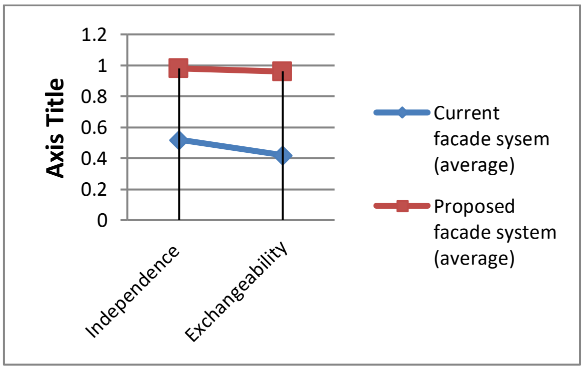


Figure 5-47: Output of the second level of the evaluation model

The above figures provide an overview that compare the results of the evaluation for the current façade system and the proposed one.

5.4.3 Assembly and construction of the proposed facades

Two types of precast demountable panels could be used as a part of a demountable façade system for the different parts of the building. The first is the vertical panel which can be fixed to the upper and lower beams. The second is the horizontal panel that can be fixed to the lower beam that transfer its load. In addition, a demountable secondary beam that laterally support the exterior panel and the interior component is required. These panels are developed based on the conventional panel system as previously discussed. This façade system has been chosen due to its suitability to this building in terms of providing a better performance and appearance. The external finish component could be used to provide the building with an exchangeable façade finish that could be change and reused as required. In addition to that flexibility of the whole façade system will be obtained. Figure 5-48, 49 and 50 provide a general overview of the construction technique of this system.

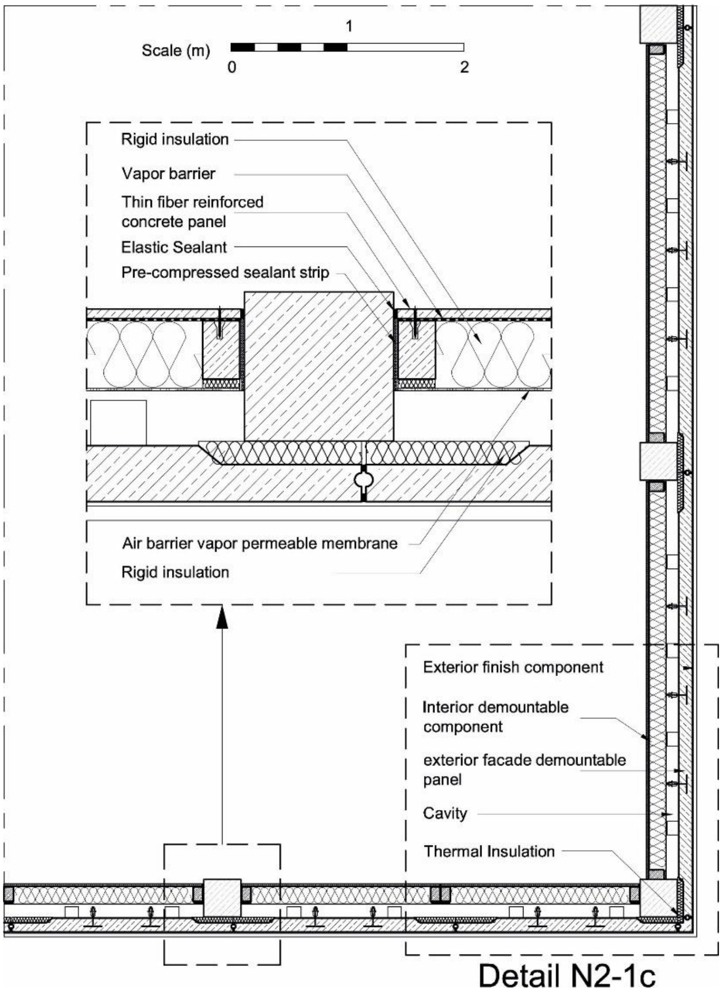


Figure 5-48: Detail N2-1b showing a horizontal section at the ground floor below the windows level

In the previous chapter the finishing component has been used with sandwich panel systems, however it could be also used with the developed conventional panel system.

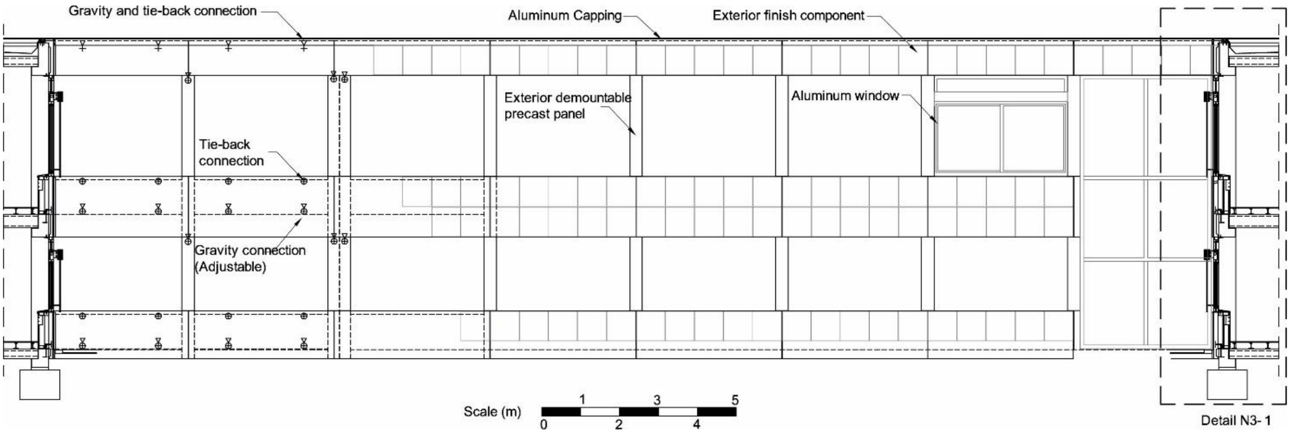


Figure 5-49: Section g-g showing the use of demountable facades and the exterior finish components and their construction.

Appendix 20 shows the new proposed system for different façades of the building and indicates a number of details that clarify the construction of these facades. It is important to mention that standardization has been utilized as much as possible to facilitate the assembly processes and to increase the reuse potential of the façades.

5.5 Conclusion

The application of the demountable facade systems in this case study has proved that demountable concrete structures could be achieved through the application of DfD aspects. The application has also confirmed that concrete faced systems are achievable and the barriers to their implementation could be overcome. The proposed façade system has not only provided the building with high disassembly potential but also with flexibility and adaptability. Through ease of disassembly and change in addition to the high reuse potential, the proposed system proved that precast concrete demountable facades are applicable.

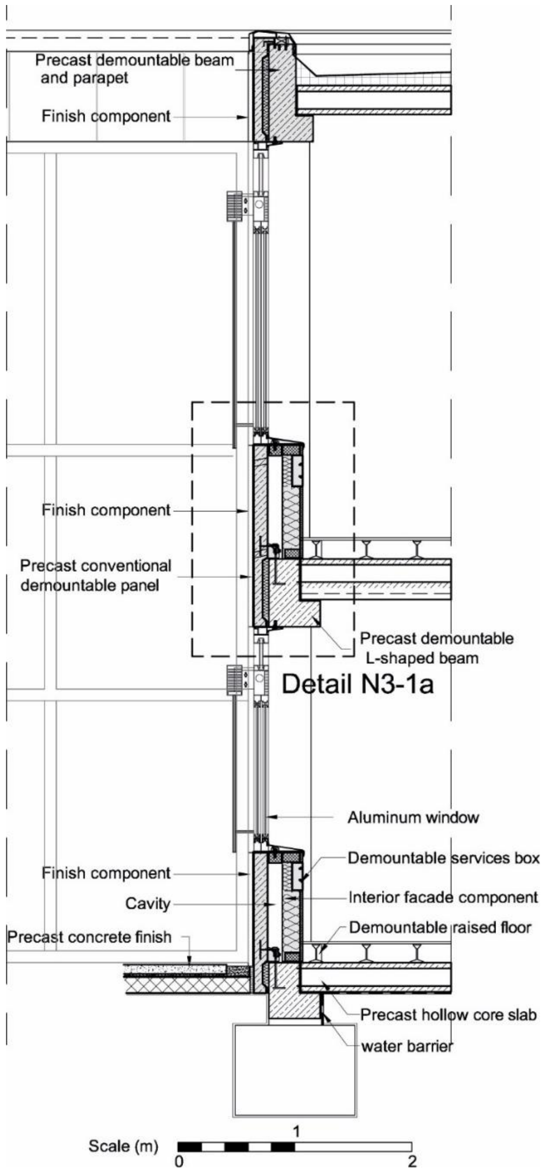


Figure 5-50: Section N3-1 showing the construction of demountable façade system

Chapter 6. Conclusions and recommendations

6.1 Conclusions regarding the construction of concrete buildings

After the revision that considered the construction of concrete buildings and its relation to the concept of design for disassembly of buildings the following aspects could be concluded:

- The construction of concrete buildings still utilizes the conventional methods and technologies which do not take the end of life of the buildings into consideration.
- The disassembly potential of concrete buildings - that are constructed using cast-in-situ construction or cement mortar to join precast elements - is very low. That can be attributed to many reasons including intensive labor work and the use of diamond saw machines to cut the elements which prove to be a non-feasible option.
- More interest should be dedicated to the link between the continuous development in concrete technology and the end of life scenario of concrete buildings and their elements.
- The demolition of concrete buildings will continue as the most visible option. Until the construction design of concrete buildings considers transformation and disassembly or a new advanced disassembly and cutting technology of concrete buildings are introduced demolition will be dominant.
- Some developed concrete technologies could be utilized for the production of demountable and reusable elements that is light in weight, strong and durable.
- However, some common precast concrete elements and systems could be disassembled; the transformation capacity which indicates the sustainability of the system could be low due to the absence of some design for disassembly aspects.
- The big sizes and heavy weights of concrete elements should not be a hindrance to design concrete buildings for disassembly as long as there are suitable handling methods and technologies.

6.2 Conclusions regarding precast concrete elements and systems

During this study, precast concrete elements and systems have been explored and analyzed with regard to their disassembly potential it can be concluded that:

- The common precast concrete elements and systems are being mainly designed for fast and ease of assembly and not for reuse and end-of-life considerations.

- Some common precast concrete elements and systems generally have some design for disassembly aspects such as mobility, functional separation, geometry and standardization. These aspects nominate them for further development as demountable, transformable elements and systems.
- However, some precast demountable systems have been developed, but they still lack important aspects regarding their transformation capacity, such as ignorance of systematization, assembly and connection aspects.
- Despite the fact that precast elements and systems proved to be a more economical and qualified option for projects with high standardization some aspects are still need to be considered. Transporting and erection of these systems could be developed to be more effective, safe and convenient.
- Precast elements of small sizes considered to be not suitable for the sake of DfD unless they were systematized and clustered into demountable components.
- The attempts to the reuse of precast concrete façade panels were very successful and feasible.
- The existing materials that are used for jointing precast elements such as elastic sealants and pre-compressed strips provide a suitable solution for jointing for future disassembly. At the contrary permanent jointing using cast-in-situ concrete expose the elements edges for damage and considered a non-suitable option.

6.3 Conclusions regarding design of concrete buildings for disassembly

The previous study and consideration of concrete buildings to be designed for disassembly resulted in the following conclusions:

- Concrete buildings could be designed for disassembly totally including the whole building physical levels or partly for specific building physical levels such as the enclosure and infill systems.
- What distinguishes concrete buildings from other types of buildings such as steel or timber is the dominance of the use of concrete to provide different functionalities to the building.
- Designing concrete buildings for disassembly is possible through precast demountable systems that take all the transformation capacity aspects into consideration.
- Reinforced concrete as a building material should not be distinguished from steel or timber regarding the ability of producing demountable elements.
- Some building types such as those that have high standardization aspects are more feasible to be DfD due to the higher reuse potential of their elements and components.
- However, erection and assembly tools for building are existing, there might be a need for the development of new tools. Such new tools should have the ability to manage the assembly of the different physical levels of the building with more convenience, speed and safety.
- Some physical levels of the building are easier to be disassembled than others due to certain distinguishing characteristics of these systems such as the functional separation.

- The structural level of the building is governed by the assembly sequence of the building elements and the gravity limitations. Such characteristics make the transformation and disassembly of this level highly restricted.
- Most of the challenges that may face the design of concrete buildings for disassembly has already a solution or can be solved through the utilization of the new technologies.
- In the future, disposal of demolished buildings is going to be more expensive due to the environmental pollution that it causes. Also, demolition is still costly and has many environmental impacts. The initial costs of designing systems for disassembly will be substitute by the ease of assembly and disassembly and the resale value of the reusable elements and components.

6.4 Recommendations and further research

As a result of this study the following recommendations are suggested to be considered by all parties of the construction sector when designing concrete buildings for disassembly.

- Design of concrete buildings for disassembly should be considered in all phases from planning to design and construction of buildings that have high standardization aspects.
- The manufacturers of precast concrete elements are advised to take the transformation capacity of their products into consideration which will contribute to increase their sustainability.
- Design of concrete buildings for disassembly should be supported by national and local governments due to the environmental and social benefits that could be obtained.
- National and local governments can support the adaptation of designing buildings for disassembly by requiring a level of disassembly potential for the various physical systems of concrete buildings to obtain a building permit for example.
- Reuse of the precast concrete elements that could be obtained from the old buildings should be considered and supported when the quality of these elements is assured.
- Precast concrete panels that are going to be designed for disassembly should consider advanced durability and multiple reuse issues.
- Design for disassembly of buildings should be integrated into the programs of the architectural and building schools as one of the sustainable design strategies.
- The knowledge model of Durmisevic needs to be revised with regard to the weights of the DfD aspects, for example the connection aspects still dominate the disassembly potential especially for concrete buildings. In addition to that the input data that is provided to the different criteria which affects the disassembly potential could be different from one expert to another. The author recommended some workshops for discussing the wright ways of choosing the input data for common systems.
- Concepts for the development of demountable infill systems including partitions and stairs are still required.

- Effective and controlled demountability technologies for cement mortar connection are still need to be developed.
- Special assembly machines (like cranes) that are capable to assemble and disassemble façade elements quickly and safely are still need to be developed.

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About the author

Wasim Salama was born in Palestine in 1980

Education and Activities

- Studied the secondary stage at Jenin secondary boys school
- Obtained his Bachelor and Master degree in Architectural engineering from An_najah N. University, Palestine.
- Worked as an Architect in various Engineering Offices in Palestine.
- Worked as teaching assistant at the Faculty of engineering at An-Najah N. University, Palestine
- Worked as a lecturer at the school of fine arts at An-Najah N. University, Palestine
- Worked as a lecturer at the department of architectural engineering at An-Najah N. University, Palestine.
- Advisor for some engineering offices in Palestine

Memberships

A member of the Jordanian Engineering association since 2004

Publications:

International Journals, Conferences

Publications by the author

Conference proceedings

1. *Transportability and adaptation through design for disassembly; the case of concrete buildings,*

The 3rd Architectural Design Conference ARCHDESIGN '16 Istanbul, Turkey June 17-18 2016.

2. *Design for disassembly as an alternative sustainable construction approach to life-cycle-design of concrete buildings,*

The Third International Green Design Conference (GCD2017) on Green Cities, Buildings and Products Mostar, (Bosnia and Herzegovina) from 04 October- 07 October 2017
Link to the proceedings http://greendesignconference.com/conference/conference-proceedings/

Journals

1. *Design of concrete buildings for disassembly: an explorative review,*

Published in the International journal of sustainable built environments in 22 April, 2017

Link to the paper: http://dx.doi.org/10.1016/j.ijsbe.2017.03.005

Appendixes

Appendix 1: Interviews

A number of personal interviews have been held with experts, Academics and practitioners, two interviews to review the proposed development systems with Dip. -Ing. Klaus-Peter Krüger from PAPENBURG precast factory and Dip. -Ing. Wolfgang Ehrenberg from BWEBAU precast factory resulted in some feed backs that have been taken into consideration. The following are some of these interviews:

Dr. Elma Durmisevic

Date of the interview: Oct. 31- Nov. 4, 2016

Occasion and place: A short research visit, University of Twente, Enschede, Netherlands

Introduction

Elma Durmisevic is an architect and a lecturer at the University of Twente in Enschede- the Netherlands she is specialist in designing buildings and building products for disassembly. Dr. Durmisevic has conducted many researches that utilize design for disassembly of buildings to prevent from demolition and to support reuse of building's parts, components and elements.

The author: *With regards to design for disassembly of concrete buildings what sides do you think need to consider for any developed demountable system for facades?*

Dr. Elma: I think some effort needs to be dedicated for the recovery options, one can think of the recovery options for the whole system, and if good valuable propositions cannot be defined for the recovery of the system level, one can think of other levels like components and parts. One can map these recovery options and try to connect them to different design strategies. One can also think about a business or financial model about that which will provide a complete picture around that.

The author: *Do you think that designing concrete buildings for disassembly will help in moving these buildings to a higher degree of sustainability?*

Dr. Elma: I understand that the aim that you want to achieve is to increase the reuse potential of concrete, but first of all you have to prove that this is a good thing to do. There are many people how would argue that we should develop alternative methods and materials which can replace concrete.

The author: *The study takes into* consideration *analysis of all physical levels of the concrete building including structural, infill and enclosure systems; however, the focus for system development* *will be dedicated to façade systems. Do you think that development of demountable concrete facades is a priority?*

Dr. Elam: I think you need to explain why did you chose the façade systems from a scientific point of view and support that with the results you have achieved from the analysis of the whole physical levels.

Dr. Elam: why do you think concrete is a good option for facades, it is heavy and facades provide the building with a number of function and concrete can satisfy a few of them?

The author: *According to the analysis that have been conducted the enclosure system has shown more positive aspects with regard to its disassembly potential such as the functional dependence, in addition to that the façade systems might have higher exchangeability rates than the structural system and a higher architectural value than the infill system.*

Dr. Elam: Why do you think concrete elements deserve to be developed for disassembly, in other meaning where did you see this potential of concrete to become more sustainable?

The author: *Some studies have shown that concrete might have lower environmental impact than steel specially when substitutions of cement are used, also the use of some concrete technologies can contribute to increase the life cycle of concrete elements and consequently their values. Other aspects such as free of off-gases and the thermal mass of concrete element are positive aspects that make concrete a preferable construction material. In addition to that designing concrete elements for disassembly will help in preventing from demolition and the associated environmental impacts.*

Dr. Elam Have you studied the life cycle assessment of concrete with respect to other building materials such as steel?

The author: *Yes, in fact many studies have been compared the life cycle assessment of concrete especially with steel, despite the fact that some but not all showed that steel has lower environmental impacts, the reason was the use of cast-in-situ concrete in most of the studies and the consideration of demolition as an only end of life scenario. Depending on the fact that precast concrete has lower environmental impact compared to cast-in-situ, and the existence of reuse option there is a great potential for opposite results and this is already proved by some studies that compared individual elements.*

Dr. Elam: Some studies *have* been made to identify the waste streams in couple of countries such as Netherlands, Belgium, Bosnia; the studies have mapped all materials coming out of buildings and showed that concrete ends up in degradation of values and its recovery option is down cycling for road base construction, and it is not in the line of European legislations and ambitions to keep material values in up cycling loops as long as possible.

The author: *That's right and that can be explained by the conventional use of concrete as a construction material. The conventional ways produce monolithic entities that can't be disassembled and the only solution is demolition and down cycle of concrete, so the case will be definitely different when DfD in addition to durability and reusability requirements are applied to concrete elements. In this case concrete elements will be more durable and reuse will replace demolition and all the negative environmental impacts are going to be neglected.*

Dr. Elma: That's right, however, to Design a building for disassembly that does not mean that its elements are automatically will be reused but there are many advantages of DfD can be find in different aspects, if you don't have to demolish a building you can just take it apart, even though the elements are not going to be reused but you can very fast without disturbing the neighborhood, without creating health issues involved. So, if DfD has just to provide these aspects any other aspects that will be added to this are added up values.

The author: *This picture shows the use of ultrahigh strength concrete in making a very slim spiral stair in Tuborg building, Copenhagen.*

Dr. Elam: In this case fiber reinforcement is used which produces a kind of composite material and the recyclability of such elements is very tricky.

The author: *Despite the fact that this element is composite but this type of reinforcement is going to increase the life cycle of the element, in addition to that if the typical down cycling method used to recover such elements the fibers resulted will be beneficial to any new reuse of the material since it will provide additional strength. However, new recycling technologies for composite materials need to be considered.*

Dr. Elam: Nowadays the tendency is toward building systems that are able to be upgradable, can be up cycled, where systems or actions that degrades or lead to degradation of values should not be allowed. Then the reuse on the same level of the functional quality of elements and components, upgrading it to something else, or upgrading the material levels of these elements and components then this follows the same philosophy.

Dipl. –Ing. Egbert Müller

Date of the interview: Feb. 14, 2017

Occasion and place: "Betontage" Concrete solutions congress, Neu-Ulm, Germany

Egbert Müller is a research assistant at the Institute of concrete, supervised by Univ.-Prof. Dr.-Ing. E. h. Manfred Curbach at Dresden University of Technology, his main task for research is carbon reinforced concrete.

The author: *How do you see the next generation of concrete buildings, from your perspective as an expert in carbon reinforcement do you think that these buildings should be demountable and reusable?*

Egbert Müller: I think to support the reuse of the concrete structure and its elements we need more effective carbon reinforcement for these elements in order to support their reuse. There are two main ways we are going with the carbon reinforcement of concrete, it can be used for new structures and elements or it can be used to strengthening existing concrete structures. Personally, I think it is really important to focus using carbon reinforced concrete to strengthening the existing buildings to prevent them from demolition. Therefore, we can provide a longer usage and life time cycle. With regards to the use of carbon reinforced concrete for the production of very slim elements in my opinion the problem of deflection should be considered.

The author: *Do you think that the use of carbon reinforcement will help in avoiding normal problems which may occur to steel reinforcement such as corrosion prone?*

Egbert Müller: Yes definitely, we don't have to consider rust anymore, because this material is corrosion resistant. As a result, we can make slim elements with carbon reinforcements because we only have to consider the concrete cover to guarantee the bond between the reinforcement and the concrete. So, we can save a lot of material in our future concrete structures.

The author: *Is the production of carbon fibers energy intensive?*

Egbert Müller: In fact, yes, the production processes required a large amount of energy especially for oxidation and carbonization processes. But overall, we will have a longer life cycle.

Prof. Dr. –Ing. Christoph Gehlen

Date of the interview: Feb. 15, 2017

Occasion and place: “Betontage” Concrete solutions congress, Neu-Ulm, Germany

Christoph Gehlen is a specialist in Materials and Materials Testing in Construction he is also interested in 3d printing with concrete and its application potential in architecture Prof. Gehlen is a lecturer at the technical university of Munich.

The author: *As an expert in construction materials and three-dimensional printing with concrete, do you see any potential for three-dimensional printing in concrete to contribute to extending the life cycle of concrete elements by producing demountable elements that can be disassembled and reused? Or it is more directed to cast in situ construction that has one end of life scenario the demolition?*

Prof. Gehlen: I see some potential because three-dimensional printing provide the ability to construct buildings or building elements with very precise geometry, where you can integrate different functionalities, into this kind of sections, and for that reason I would say if the material that we will print with different techniques is durable, then sustainable construction can be built with this kind of methods.

The author: *Do you think that the next generation of concrete buildings should be designed for disassembly and reuse of its elements and parts?*

Prof. Gehlen: Yes, the tendency is to do and follow this approach in that direction and to say once again precise geometry is one major task to promote this kind of thinking about reusable elements not only on recycling concrete but also recycling concrete elements for example to rebuild something different with elements which are already printed.

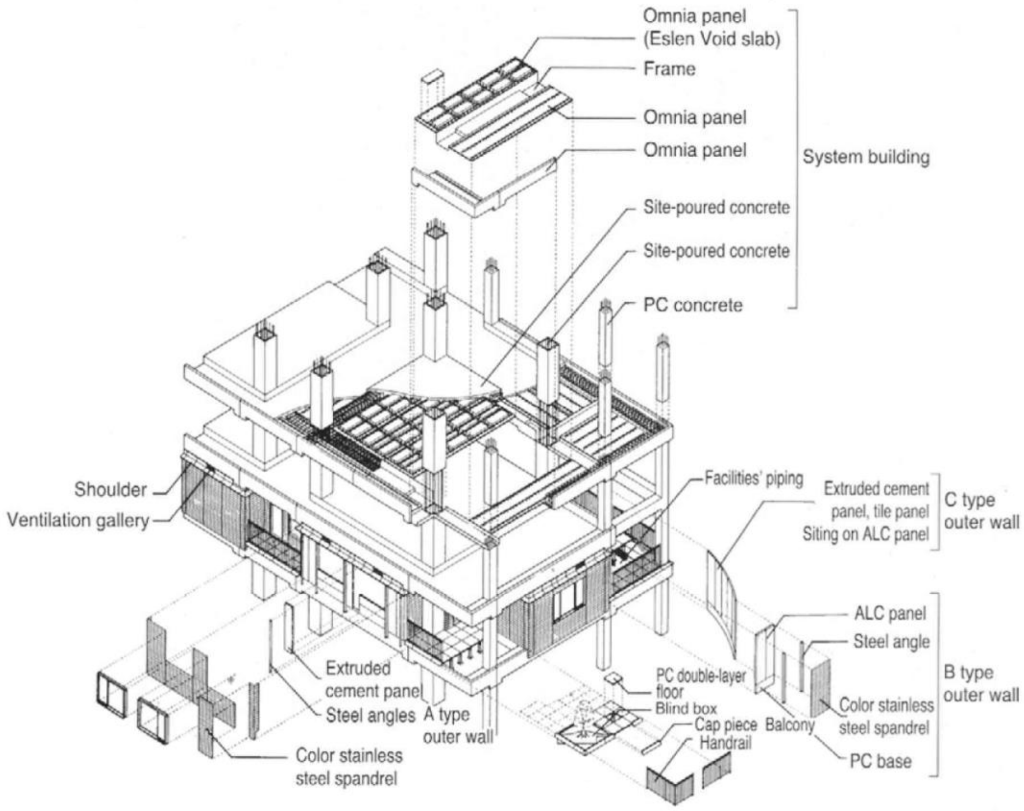
Appendix 2: Questionnaire

Design of concrete buildings for disassembly

This survey aims to support a PhD study on Design of concrete buildings for disassembly by exploring the specialist and experts opinions about the ability and limitations of concrete as a building material to contribute to the life-cycle design of buildings based on the design for disassembly.

* Required

1. **Email address ***



The construction of concrete buildings

This section is dedicated to exploring replies regarding the current construction of concrete building and its response to society needs and future innovations.

3. **The construction of the concrete buildings is considered conservative and lacks innovations and change, how much do you agree?** *

Mark only one oval.

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree

4. **Do you consider designing concrete buildings for disassembly to facilitate adaptation and reuse of its elements and materials add value to the building? (Multiple checks are possible)** *

Check all that apply.

- [ ] No
- [ ] Yes, environmental values
- [ ] Yes, economical values
- [ ] Not Sure

5. **Do you see that the current construction of concrete buildings responses to the sustainability in terms of conserving natural resources especially with the dominance of demolition as an end of life scenario?** *

Mark only one oval.

- Yes
- No
- Maybe

6. **Demolition is the dominant end of life scenario for concrete buildings; it prevents from reuse of their elements and causes material loss, pollution, and disturbance of life activities around the site, how much do you agree that demolition must be considered as a design error that needs to be considered?** *

Mark only one oval.

- strongly disagree
- Disagree
- Neutral
- Agree
- strongly Agree

7. **The concrete buildings are constructed either using cast-in-site concrete or precast systems, do you see that these systems could have answers regarding reuse and recycle of materials and elements in the buildings of the future? (Multiple checks are possible)** *
Check all that apply.

- [ ] Yes, both systems could have answers
- [ ] Precast systems are more likely to have answers
- [ ] Cast-in-place are more likely to have answers
- [ ] But more development of the system is needed
- [ ] No

8. **The precast concrete systems and cast-in-site concrete are two different ways of constructing buildings, which do you think is more environmentally friendly in terms of quality, conservation of resources, prevention of waste and pollution?** *
Mark only one oval.

- Precast systems
- Cast-in-place concrete
- Don't Know

Life-cycle of concrete buildings

This section explores replies regarding the concept of circular buildings and to what degree concrete buildings might response to such concept.

9. **In many cases concrete buildings are demolished after 15 or 20 years to make room for other buildings that differ in type or size to be constructed. What do you think about its elements and components at the time of demolition (not only those that face demolition after 20 years but in general)** *
Mark only one oval.

- The concrete elements have a longer technical life and can serve more time
- The concrete elements are exhausted and can serve no more
- don't know

10. **If concrete buildings have been designed for disassembly, their elements and components could be recovered by reuse, down-cycle or recycle, do you think that the reuse options for these elements and components are** *
Mark only one oval.

- Multiple and various
- Limited
- Very limited
- Don't Know

11. **Extending the concrete elements life may require the use of special additives or admixtures to increase its strength and durability, do you think that using such materials affects significantly the production cost of these elements?** *
Mark only one oval.

- Yes
- No
- Maybe

12. **Disassembly could replace demolition of concrete buildings and reduce material loss, however, some additional initial costs are expected, to what level do you agree that the value of the elements would be greater in the future?** *

Mark only one oval.

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree

13. **How much do you agree that buildings considered as "material banks" and concrete elements and components are valuable parts that need to be designed for disassembly and reuse?** *

Mark only one oval.

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree

Precast concrete systems

This section is dedicated to exploring replies regarding the applications of precast systems in building construction, their contribution to the sustainability of the building and the effect of designing them for disassembly

14. **Review of the attempts that have been done to reuse concrete elements showed that the case of precast wall panels was successful. How much do you agree that all building elements including footings, columns, beams, and slabs could be reused if they were designed for disassembly** *

Mark only one oval.

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree

15. **Do you think that designing precast concrete elements and systems for disassembly would encourage more adoption of these system in the construction of buildings?** *

Mark only one oval.

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree

16. **Concrete elements are heavy compared to other elements from other materials such as steel and timber that do the same function, do you think that this should shape a hindrance to designing concrete buildings for disassembly?** *

Mark only one oval.

- Yes
- No
- Maybe

17. **Do you think that the size of precast concrete elements should shape a hindrance that might prevent from reuse of these elements?** *

Mark only one oval.

- Yes
- No
- Maybe

18. **The design of precast elements for disassembly and reuse required a kind of standardization of element edges and connection to increase their use and reuse potential, how much do you think this may limit the creativity in architectural design?** *

Mark only one oval.

- Very little
- Little
- Neutral
- much
- Very much

Design for disassembly

This section is dedicated to exploring replies on design for disassembly of concrete buildings and connection between theory and practice.

19. **Do you think that concrete buildings should be designed for disassembly of its elements and materials despite some economic and technical challenges?** *

Mark only one oval.

- Yes
- No
- Maybe

20. **The design of concrete buildings for disassembly will provide the building with exchangeable facades, partitions, and services- without material loss-, how much do you agree that this is important to the buildings of the future?** *

Mark only one oval.

- Very important
- Important
- Neutral
- Not important
- Not important at alll

21. **Do you think that design of buildings for disassembly should be integrated into the education programs of engineering and architectural schools?** *

Mark only one oval.

- Yes
- No
- Maybe

Concrete technologies

This section is dedicated to exploring replies on the connections that could be established between developed concrete technologies and the end of life phase of buildings.

22. **How much do you agree that the new developed concrete technologies such as ultra strength concrete, light weight concrete, self-compacted concrete, etc. should be connected to the end of life phase of buildings by using it in designing elements that are durable and have very high disassembly potential.** *

Mark only one oval.

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree

23. **Do you think that the continuous development of the concrete technologies will provide precast systems with more lightness and strength that increase its durability and encourage their reuse?** *

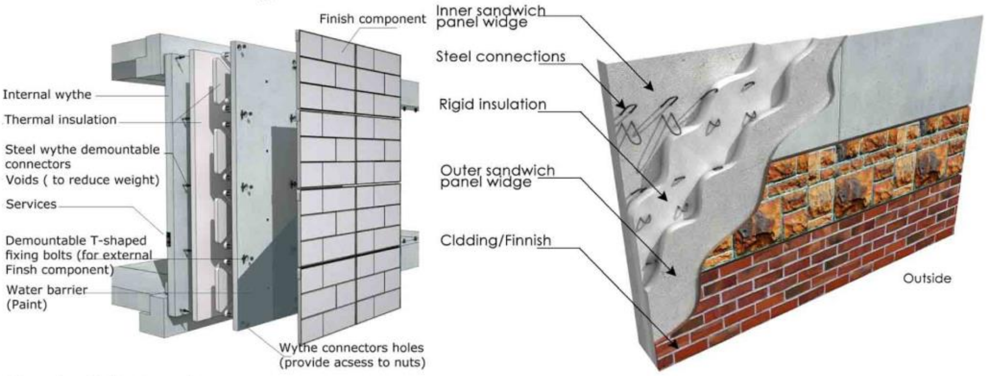
Mark only one oval.

- Yes
- No
- Maybe

Concepts for development of precast systems

This section explores replies on some concepts that have been developed to provide some existed precast facade systems with high disassembly potential.

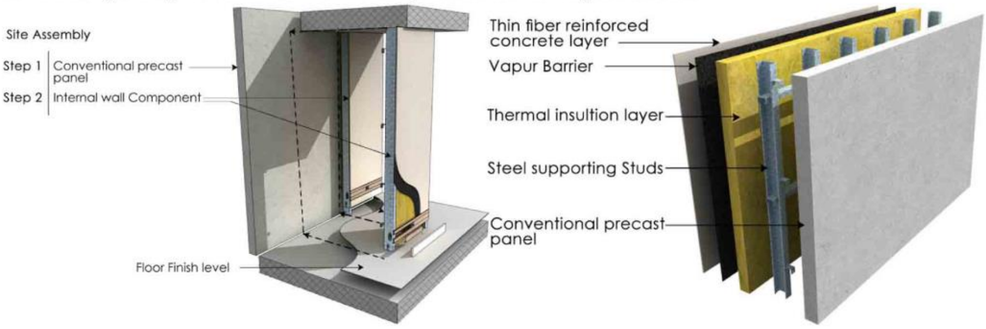
24. **The following figure shows a development concept to emancipate materials level of a precast sandwich panel for reuse and recovery of the system or its parts, what do you think about the following** *



Check all that apply.

- [ ] The concept of development provide a higher value to the system
- [ ] The system and its parts could be reused for various applications in construction
- [ ] This development prevent from material loss
- [ ] The old sandwich panel has higher value
- [ ] The cost of production may be affected significantly
- [ ] I don't find the development useful.

25. **Precast conventional panel system could be developed to have high disassembly potential of its elements and materials by including components instead of individual materials, which simplify and speed the processes of assembly and disassembly, how much do you agree with these developments in the figure below** *



Mark only one oval.

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly agree

26. **Do you think that the developments that provide facade systems with high disassembly potential, and high exchange-ability and transformation capacity can bridge the gap between theory and practice regarding design for disassembly of concrete buildings?** *

Mark only one oval.

- Yes
- No
- Maybe

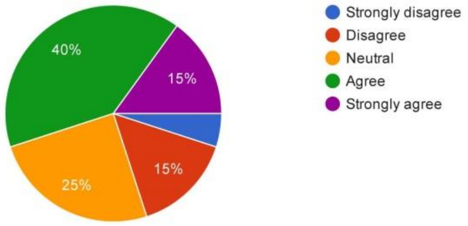
Design of concrete buildings for disassembly

20 responses

The construction of concrete buildings

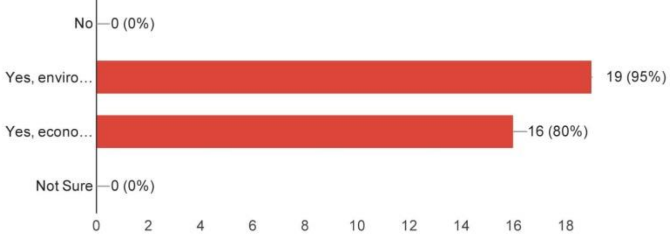
The construction of the concrete buildings is considered conservative and lacks innovations and change, how much do you agree?

(20 responses)



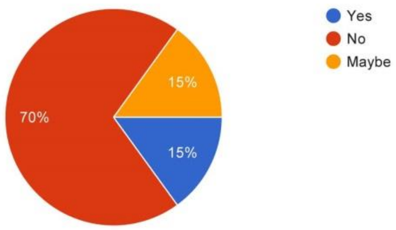
Do you consider designing concrete buildings for disassembly to facilitate adaptation and reuse of its elements and materials add value to the building? (Multiple checks are possible)

(20 responses)



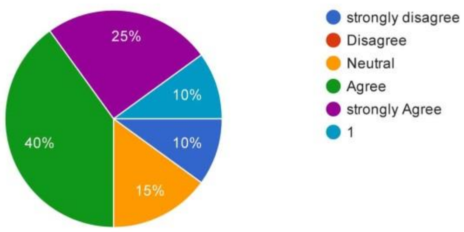
Do you see that the current construction of concrete buildings responses to the sustainability in terms of conserving natural resources especially with the dominance of demolition as an end of life scenario?

(20 responses)



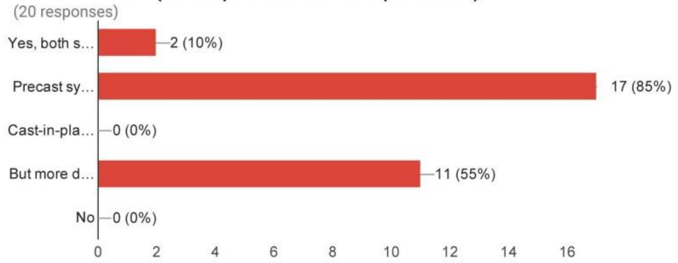
Demolition is the dominant end of life scenario for concrete buildings; it prevents from reuse of their elements and causes material loss, pollution, and disturbance of life activities around the site, how much do you agree that demolition must be considered as a design error that needs to be considered?

(20 responses)



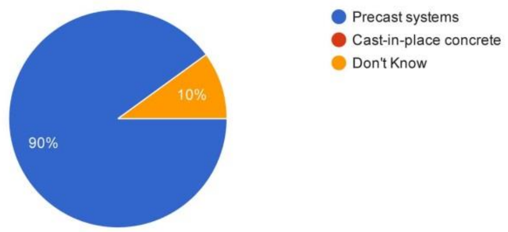
The concrete buildings are constructed either using cast-in-site concrete or precast systems, do you see that these systems could have answers regarding reuse and recycle of materials and elements in the buildings of the future? (Multiple checks are possible)

(20 responses)



The precast concrete systems and cast-in-site concrete are two different ways of constructing buildings, which do you think is more environmentally friendly in terms of quality, conservation of resources, prevention of waste and pollution?

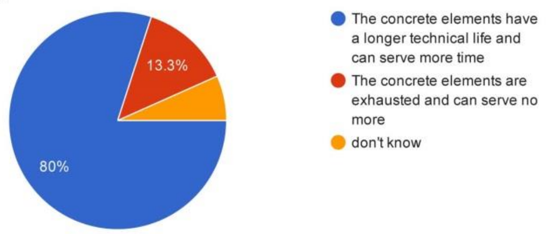
(20 responses)



Life-cycle of concrete buildings

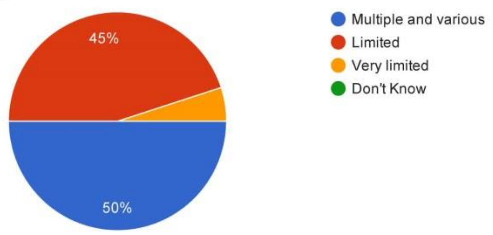
In many cases concrete buildings are demolished after 15 or 20 years to make room for other buildings that differ in type or size to be constructed. What do you think about its elements and components at the time of demolition (not only those that face demolition after 20 years but in general)

(15 responses)

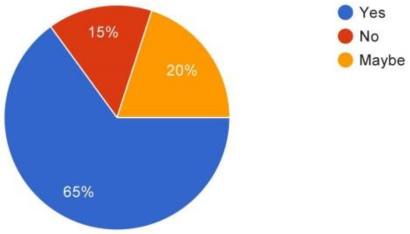


If concrete buildings have been designed for disassembly, their elements and components could be recovered by reuse, down-cycle or recycle, do you think that the reuse options for these elements and components are

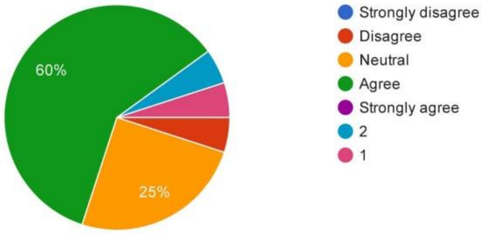
(20 responses)



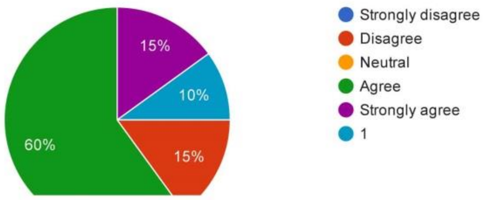
Extending the concrete elements life may require the use of special additives or admixtures to increase its strength and durability, do you think that using such materials affects significantly the production cost of these elements?
(20 responses)



Disassembly could replace demolition of concrete buildings and reduce material loss, however, some additional initial costs are expected, to what level do you agree that the value of the elements would be greater in the future?
(20 responses)

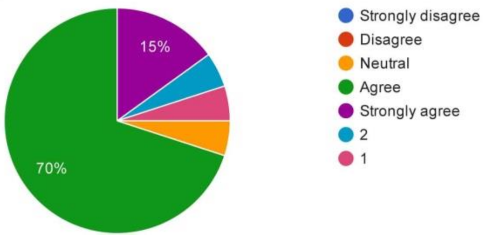


How much do you agree that buildings considered as "material banks" and concrete elements and components are valuable parts that need to be designed for disassembly and reuse?
(20 responses)



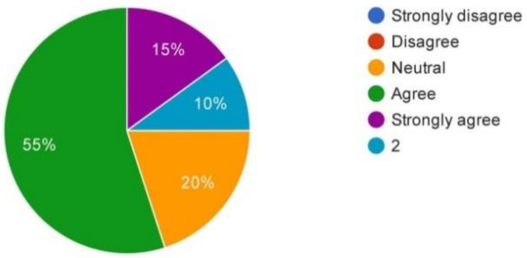
Precast concrete systems

Review of the attempts that have been done to reuse concrete elements showed that the case of precast wall panels was successful. How much do you agree that all building elements including footings, columns, beams, and slabs could be reused if they were designed for disassembly
(20 responses)



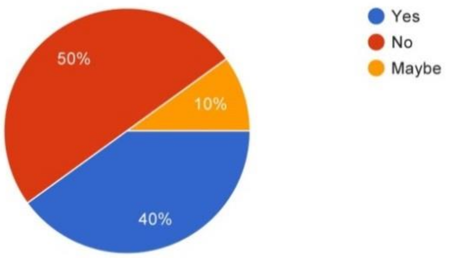
Do you think that designing precast concrete elements and systems for disassembly would encourage more adoption of these system in the construction of buildings?

(20 responses)



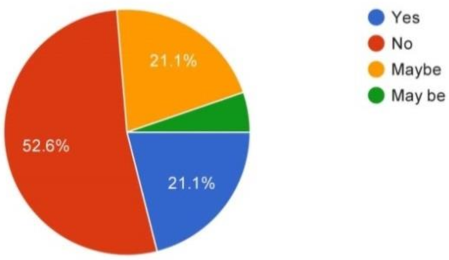
Concrete elements are heavy compared to other elements from other materials such as steel and timber that do the same function, do you think that this should shape a hindrance to designing concrete buildings for disassembly?

(20 responses)



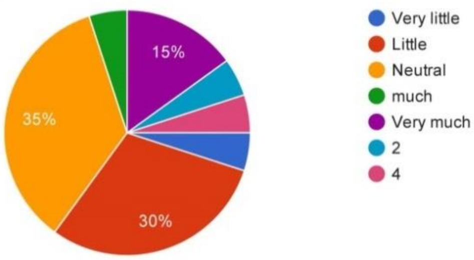
Do you think that the size of precast concrete elements should shape a hindrance that might prevent from reuse of these elements?

(19 responses)



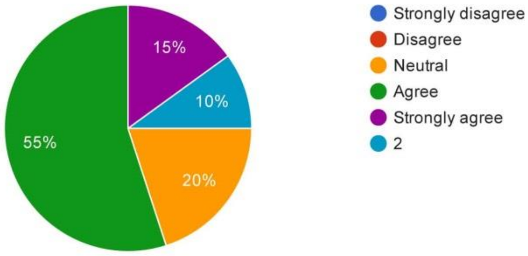
The design of precast elements for disassembly and reuse required a kind of standardization of element edges and connection to increase their use and reuse potential, how much do you think this may limit the creativity in architectural design?

(20 responses)



Do you think that designing precast concrete elements and systems for disassembly would encourage more adoption of these system in the construction of buildings?

(20 responses)



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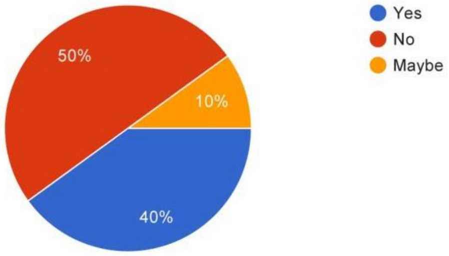
(20 responses)



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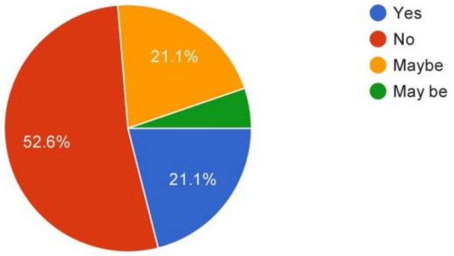

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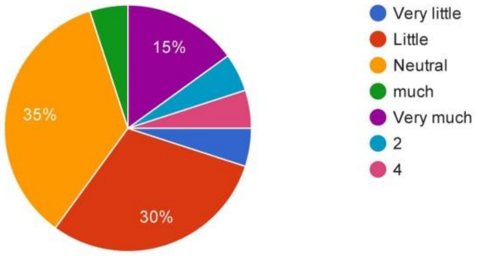
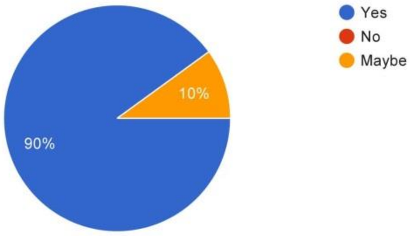
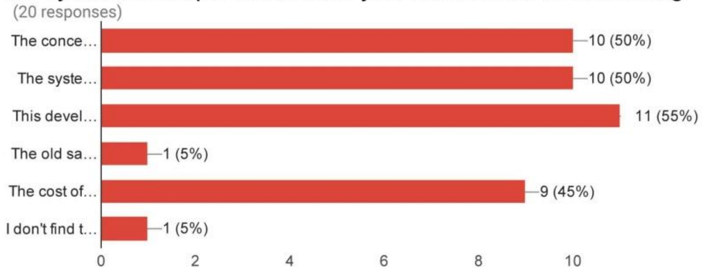


Do you think that the continuous development of the concrete technologies will provide precast systems with more lightness and strength that increase its durability and encourage their reuse?
(20 responses)

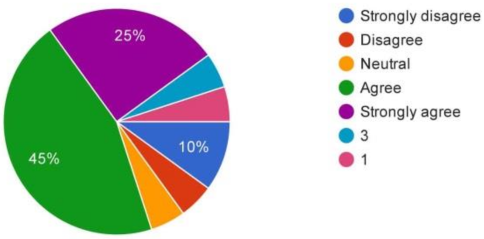


Concepts for development of precast systems

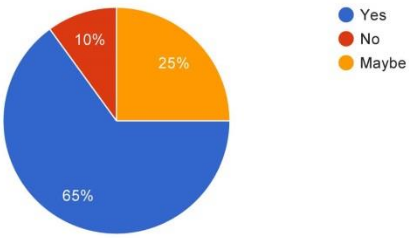
The following figure shows a development concept to emancipate materials level of a precast sandwich panel for reuse and recovery of the system or its parts, what do you think about the following
(20 responses)



Precast conventional panel system could be developed to have high disassembly potential of its elements and materials by including components instead of individual materials, which simplify and speed the processes of assembly and disassembly, how much do you agree with these developments in the figure below
(20 responses)



Do you think that the developments that provide facade systems with high disassembly potential, and high exchange-ability and transformation capacity can bridge the gap between theory and practic
regarding design for disassembly of concrete buildings?
(20 responses)



Appendix 3: Life cycle coordination matrix

building el.	service L.C.	use L.C.
foundation	75	75
load bearing exte	75	75
load bearing inter	75	75
floors	75	75
staircases	75	75
roof	75	75
façade	75	75
façade doors wi	35	75
roof finishing	20	75
roof windows	50	75
partitioning walls	75	75
wall finishing's	75	75
internal doors	75	75
floors finishing	60	75
sealing finishing	60	75
heating installatio	35	75
watervoorzining	35	75
ventilation system	25	75
electrc system	35	75

building el.	service L.C.	use L.C.
foundation	75	75
load bearing exte	75	75
load bearing inter	75	75
floors	75	75
staircases	75	75
roof	75	75
façade	75	75
façade doors wi	35	75
roof finishing	20	75
roof windows	50	75
partitioning walls	75	10
wall finishing's	75	10
internal doors	75	10
floors finishing	60	20
sealing finishing	60	10
heating installatio	35	25
watervoorzining	35	25
ventilation system	25	25
electrc system	35	10

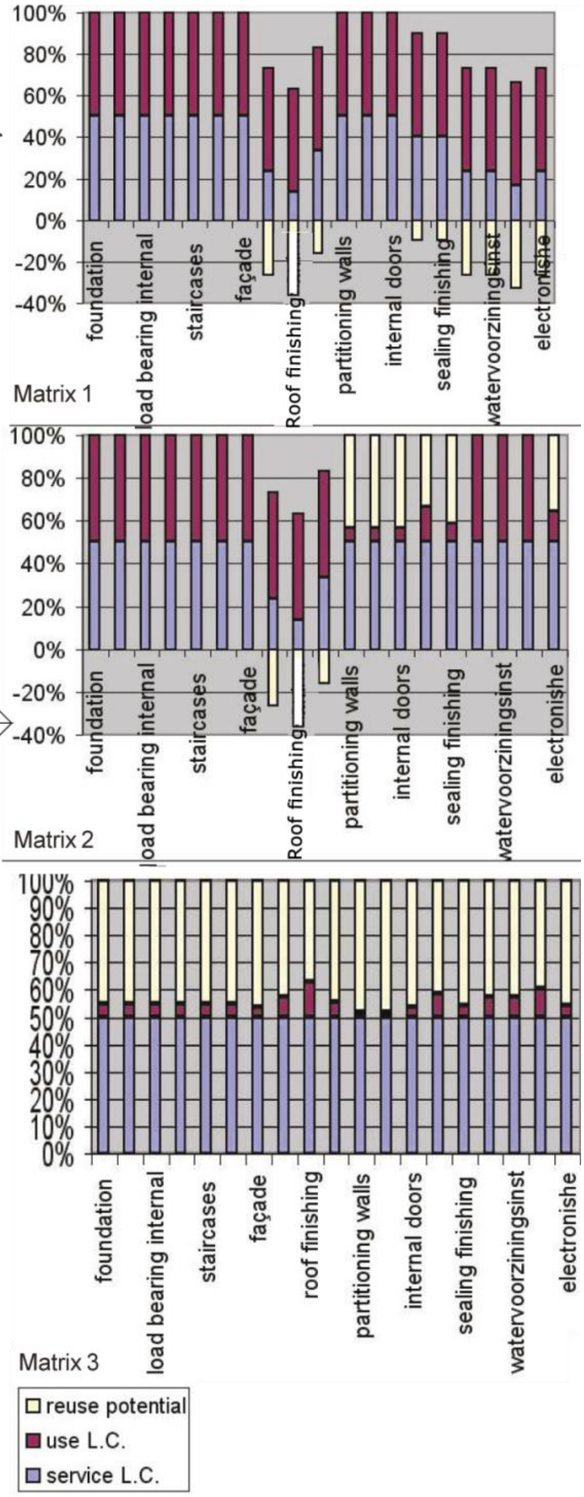


Figure A- 1: Lifecycle coordination matrix of three different types of projects regarding use potential of its components (Durmisevic 2010)

Appendix 4: Assembly types

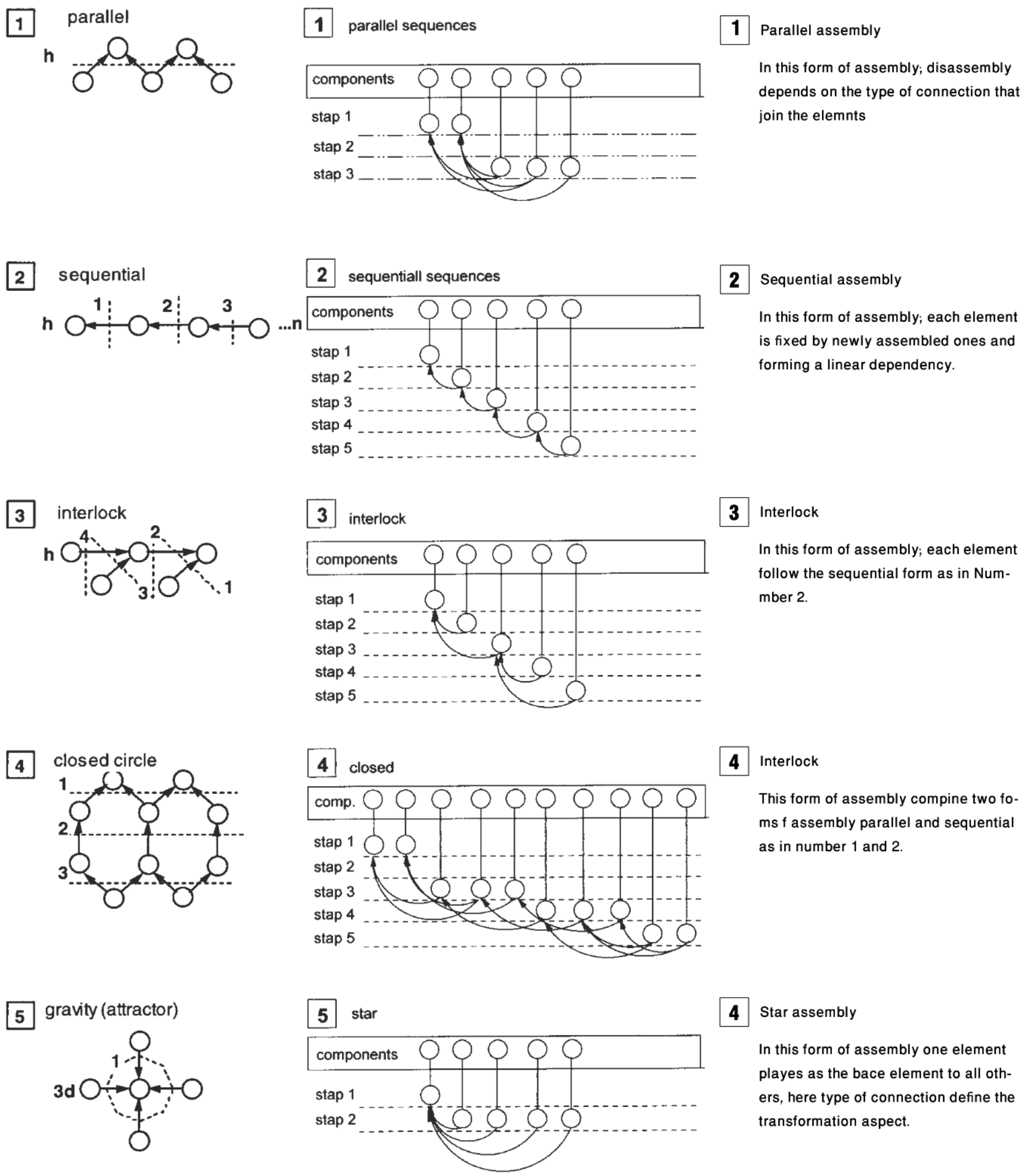


Figure A- 2: Different types of assembly relations. The assembly direction is the base for variations (Durmisevic, 2010)

Appendix 5: Types of connections

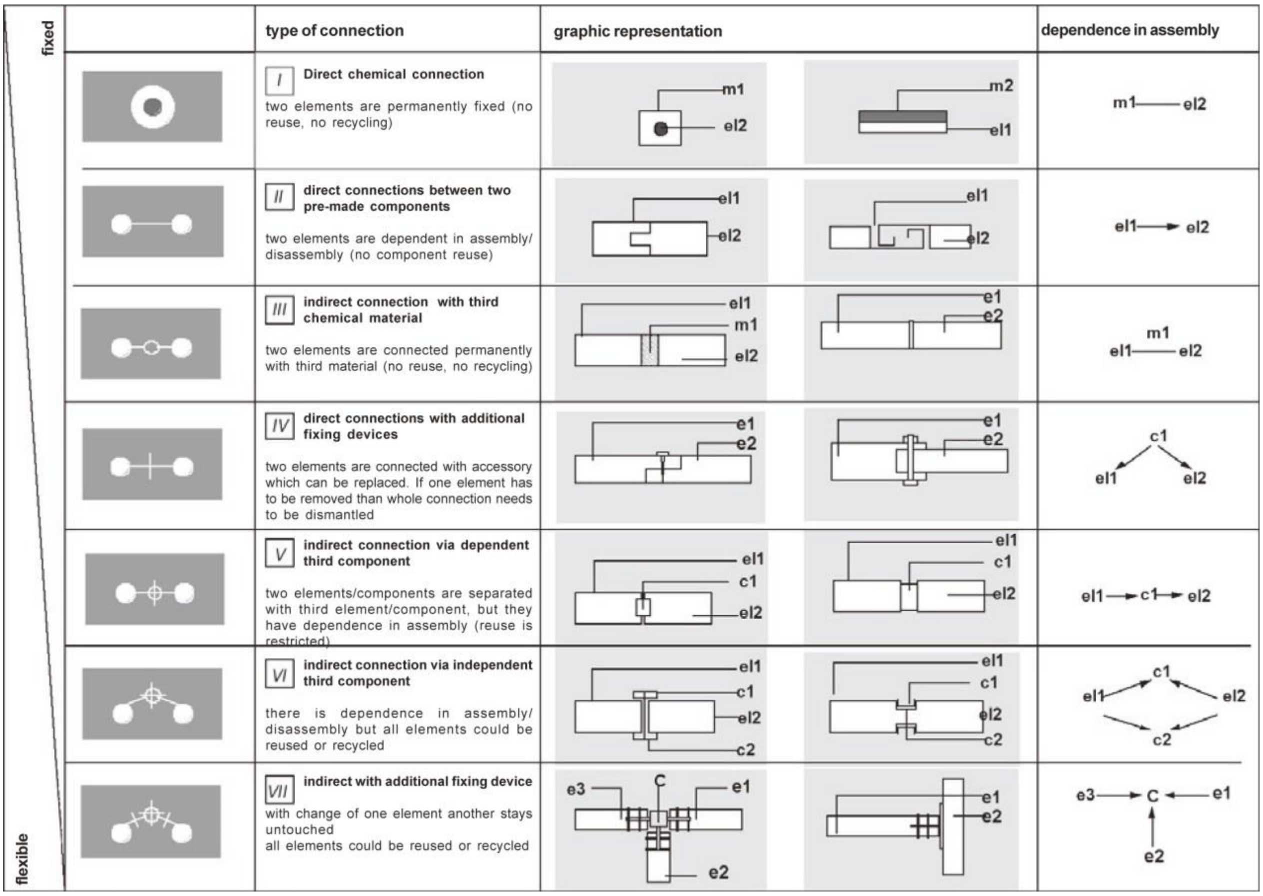


Figure A- 3: Different types of connections range from fixed to flexible.

Appendix 6: DfD aspects

DfD aspects and sup-aspects

	DfD aspect	Abbreviation	Determining factor (D.F.)
1	FD (Functional decomposition	fs	Functional separation
		fdp	Functional dependence
2	SY (Systematization	st	Structure and material levels
		c	Clustering
3	BE (Base element)	b	Base element specification
4	LCC (Life cycle coordination)	ucl	Use life cycle coordination
		tcl	Technical life cycle coordination
		s	Coordination of life cycle and size
5	RP (Relational pattern)	r	Type of relational pattern
6	A (Assembly process)	ad	Assembly direction
		as	Assembly sequence
7	G (Geometry)	gp	Geometry of product edge
		spe	Standardization of product edge
8	C (Connection)	tc	Type of connection
		af	Accessibility to fixing
		tc	Tolerance
		mj	Morphology of joint

Appendix 7: The knowledge model of Durmisevic

Evaluation of functional decomposition, systematization, base element specification and life cycle coordination of building assemblies with respect to independence and exchangeability of components

FD	functional separation	fs 01	Separation of functions	1
Functional decomposition		fs 02	Integration of functions with same LC into one element	0.6
		fs 03	integration of functions with different LC into one element	0.1
		fs= (fs1 + fs2+…… fs(n))/n		
	functional dependence	Fdp 01	Modular zoning	1
		Fdp 02	Planed interpenetrating for different solutions (Overcapacity)	0.8
		Fdp 03	Planed interpenetrating for one solution	0.4
		Fdp 04	Unplanned interpenetrating	0.2
		Fdp 05	Total dependence	0.1
	fdp= (fdp1+fdp2+….fdp(n))/n			
	FD= Fuzzy calculation based on "fs" and "fdp" and their weighting factors			
SY	Structure and material levels	st 01	Components	1
Systematization		st 02	Elements/Components	0.8
		st 03	Elements	0.6
		st 04	Material/Element/Component	0.4
		st 05	Material/Element	0.2
		st 06	Material	0.1
		st=(St1+st2+…st(n))/n		
	Clustering	c 01	Clustering according to the functionality	1
		c 02	Clustering according to the material life cycle	0.6
		c 03	Clustering for fast assembly	0.3
		c 04	no clustering	0.1
	c=(c1+c2+…=c(n))/n			
	SY=fuzzy calculation based on "st" and "c" and their weighting factors			
BE	Base element specification	b 01	Base element intermediary between systems and components	1
Base element		b 02	Base element on two levels	0.6
		b 03	element with two functions	0.3

		b 04	No base element	0.1
	b=(b1+b2+…+b(n))n			
	b=fuzzy calculation based on "b"and its weighting factors			
LCC	Use life cycle coordination (1)-Assembles first (2)- Second	ulc 01	long LC (1)/ long LC (2) or short LC (1) short LC (2)	1
Life cycle coordination		ulc 02	Long L.C. (1)/ short L.C. (2)	0.8
		ulc 03	Medium L.C. (1) / long L.C. (2)	0.6
		ulc 04	Short L.C. (1) / medium L.C. (2)	0.3
		ulc 05	Short L.C. (1) / long L.C. (2)	0.1
	ulc=(ulc1+ulc2+…ucl(n))/n			
	Technical life cycle coordination	tcl 01	Long L.C. (1)/ long L.C. (2) or short (1)/ short2 or long (1) short (2)	1
		tcl 02	Medium L.C. (1) / long L.C. (2)	0.5
		tcl 03	Short L.C. (1)/ medium (2)	0.3
		tcl 04	Short L.C.1/ short (2)	0.1
	tlc=(tcl1+tlc2+…+tlc(n))/n			
LCC	Life cycle of components and elements in relation to the size (1) Assembled first	s 01	Small element (1)/ short L.C. or medium component (1)/ short LC	1
Life cycle coordination		s 02	Big component (1)/ long L.C.	1
		s 03	Big (small element (1)/ long L.C.	0.8
		s 04	Big component (1)/short L.C.	0.4
		s 05	Material (1)/short L.C.	0.2
		s 06	Big element/ short L.C. or material/ short L.C.	0.1
	s=(s1+s2+…+s(n))/n			
	LCC= Fuzzy calculation based on "ulc"."tlc" and "s" and their weighting factors			
RP	Position of relations in relational diagram	r 01	Vertical	1
Relational patern		r 02	Horizontal in lower zone in the diagram	0.6
		r 03	horizontal between upper and lower zone of the diagram	0.4
		r 04	Horizontal in upper zone	0.1
	r=(r1+r2+…+r(n))/n			
	RP= Fuzzy calculation based on "r" and its weighting factors			
A		ad 01	Parallel - open assembly	1

Assembly	Assembly direction based on assembly type	ad 02	Stuck assembly	0.6
		ad 03	Base el. In stuck assembly	0.4
		ad 04	sequential seq. base el.	0.1
		ad=((ad1+ad2+…+ad(n))/n		
	Assembly sequence regarding material levels (1)- Assembled first (2)- Assembled second	as 01	Component (1)/ component (2)	1
		as 02	Component (1)/ element (2)	0.8
		as 03	Element (1)/ component (2)	0.6
		as 04	Element (1)/ element (2)	0.5
		as 05	material (1)/ component (2)	0.3
		as 06	Component (1)/ material (2)	0.2
		as 07	Material (1)/ material (2)	0.1
	as=(as1+as2+…+as(n))/n			
	A= Fuzzy calculation based on"ad"and "as" and their weighting factors			
G	Geometry of product edge	gp 01	Open linear	1
Geometry		gp 02	Symmetrical overlapping	0.8
		gp 03	Overlapping on one side	0.7
		gp 04	Unsymmetrical overlapping	0.4
		gp 05	Insert in one side	0.2
		gp 06	Insert on two sides	0.1
		gp=(gp1+gp2+…+gp(n))/n		
	Standardization of product edge	spe 01	Premade geometry	1
		spe 02	Half standardized geometry	0.5
		spe 03	Geometry made on the construction site	0.1
	spe=(spe1+spe2+…spe(n)/n			
	gG= Fuzzy calculation based on "gp" and"spe" and their weighting factors			
C	Type of connection	tc 01	Accessory external connection or connection system	1
Connections		tc 02	Direct connection with additional fixing devices	0.8
		tc 03	Direct integral connection with inserts bin	0.6
		tc 04	Direct integral connection	0.5
		tc 05	Accessory internal connection	0.4

		tc 06	Filled soft chemical connection	0.3
		tc 07	Filled hard chemical connection	0.2
		tc 08	Direct chemical connection	0.1
	tc=(tc1+tc2+…tc(n))/n			
	Accessibility to fixing and intermediary	af 01	Accessible	1
		af 02	Accessible with additional operation which causes no damage	0.8
		af 03	Accessible with additional operation/ causes reparable damage	0.6
		af 04	Accessible with additional operation / causes partly reperable damage	0.4
		af 05	Not accessible total damage of both elements	0.1
	af=(af1+af2+…+af(n))/n			
	Tolerance	t 01	High tolerance	1
		t 02	Minimum tolerance	0.5
		t 03	No tolerance	0.1
	t=(t1+t2+…+t(n))/n			
	Morphology of joint	mj 01	Knot (3D connections)	1
		mj 02	Point	0.8
		mj 03	liner (1D connection)	0.6
		mj 04	service (2D connection	0.1
	mc=(mc1+mc2+…+mc(n))/n			
	C= Fuzzy calculation based on "tc", "af", "t" and "mc" and their weighting factors			

Appendix 8: Magnate anchors and fasteners

Round Base - NB : Multipurpose all-weather powerful pot magnet

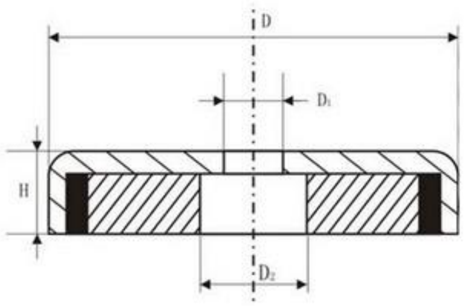
RBM-NB Series

Round Base holding pot magnet with capscrew hole

- Low-profile magnets with a capscrew hole. Made of normal grade Neodymium magnets for operating temperatures ~ max 80 Deg C.
-

An invaluable fixturing tool for fabricators and engineers who may be looking for an attractive mechanism to clamp any article to a steel base

RBM-NB Series Data Sheet : Round-Base Series



All Dimensions are in 'mm'

Type	D	D_1	D_2	H	Weight (gms)	Adhesive Force (kg)
RBM-NB16	16	3.5	6.5	5	6	4
RBM-NB20	20	4 .5	8	7	13	6
RBM-NB25	25	5.5	9	8	23	14
RBM-NB32	32	5.5	9	8	36	23
RBM-NB36	36	6.5	11	9	50	29
RBM-NB42	42	6.5	11	9	73	32
RBM-NB48	48	8.5	15	11.5	114	63
RBM-NB60	60	8.5	15	15	240	95
RBM-NB75	75	10.5	18	18	471	155

Related Products

Round Base - NA : Multipurpose all-weather powerful pot magnet

Round Base - NC : Multipurpose all-weather powerful pot magnet

Round Base - ND : Multipurpose all-weather powerful pot magnet

Round Base - NE : Multipurpose all-weather powerful pot magnet

Figure A- 4: Powerful pot magnate specifications and related products (Lifton Magnates, 2017)

PM MITEE-BITE™

MULTI PURPOSE GRIPPER WITH EYE-BOLT

FEATURES

- Compact light-weight CAM operated low-profile versatile anchoring, clamping & gripping permanent magnet.
- Ideal for underwater salvage, pilot ladder anchor, buoy marking operations, temporarily suspending bulky equipment & machinery underwater & for quick clamping & anchoring to steel parts.
- Tough construction, Steel, power-coated, Nickel-Copper-Nickel coating for corrosion resistance, marine grade, anti-corrosion treatment.
- To be used as a supplementary anchor for easy removal after job is complete.
- Maximum vertical pull forces of 400 Kg (MB400 : SWL 200Kg at 2xSafety), 600 Kg (MB600 : SWL 300Kg at 2xSafety) or 800 Kg (MB800 : SWL 400Kg at 2xSafety) on 50mm MS Plates.

Product Code : MB

All dimensions are in mm.

Model No.	Overall Dimensions (mm)	Magnet contact area (mm)	Max Pull Force (Kgs)	Rated Capacity (Kgs) at 2:1 Safety	Nett Weight (Kgs)
MB-400	400 x 110 x 40	250 x 90	400	200	4
MB-600	400 x 200 x 40	180 x 180	600	300	6
MB-800	450 x 250 x 40	200 x 200	800	400	8

PM BEAR-CLAW™

UNDERWATER SALVAGE AND GENERAL PURPOSE ANCHORING MAGNET

FEATURES

- Compact & Lightweight anchor magnet, ideal for underwater salvage operations,
- Hang various tools & equipment overhead without need for welding any temporary hooks.
- Clamping force can be designed from 100 to 400 Kg (on 50mm thick MS Plate).
- Simply lift the lever handle to separate the magnet from the steel. Use the screw-pin for forcing an air-gap if the lever operating force is too much.
- Comes with M10 & M8 eye-bolts for hanging convenience. Easy to operate!
- Dimensions: L 300mm (handle) x W 200mm (cross-bar) - T-shape.
- Nett Weight: 1.5 Kg.

HOLDING / ANCHORING / FITTING

Enquiries: info@liftonmagnets.com

www.liftonmagnets.com

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Figure A- 5: Sample of light weight anchor magnate and their specifications, dimensions and capacity (Lifton Magnates, 2017)

Appendix 9: Highlights from book “The dream of the factory-made house: Walter Gropius and Konrad Wachsmann

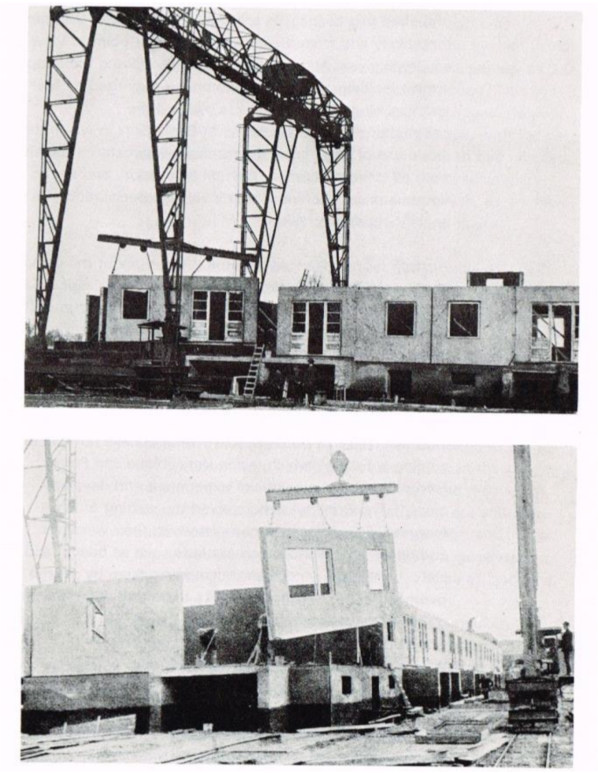


Figure A- 6: Brno System, housing estate. Berlin, c. 1926

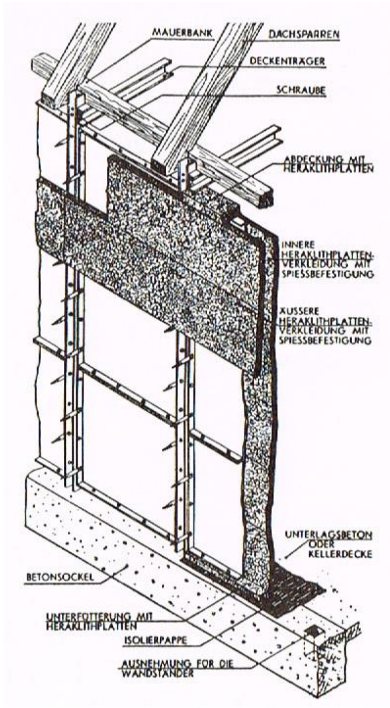


Figure A- 8: Böhler-Stahlbau, schematic diagram, lightweight system, c. 1932

Figure A- 7: Ernst May, the Frankfurt building panel factory system

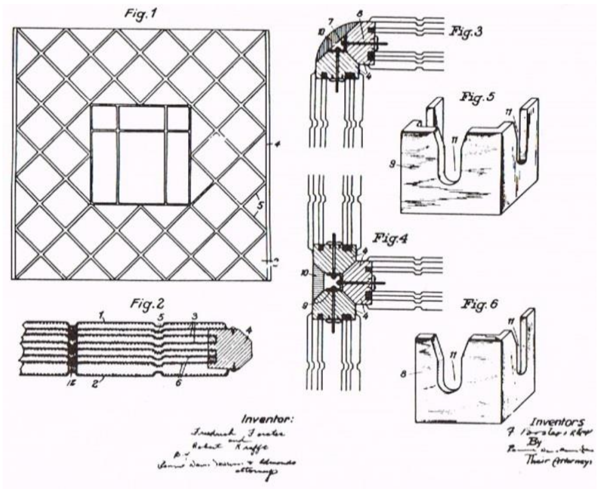


Figure A- 9: Förster and Krafft, Heat-insulating wall (U.S. patent application, 1930)

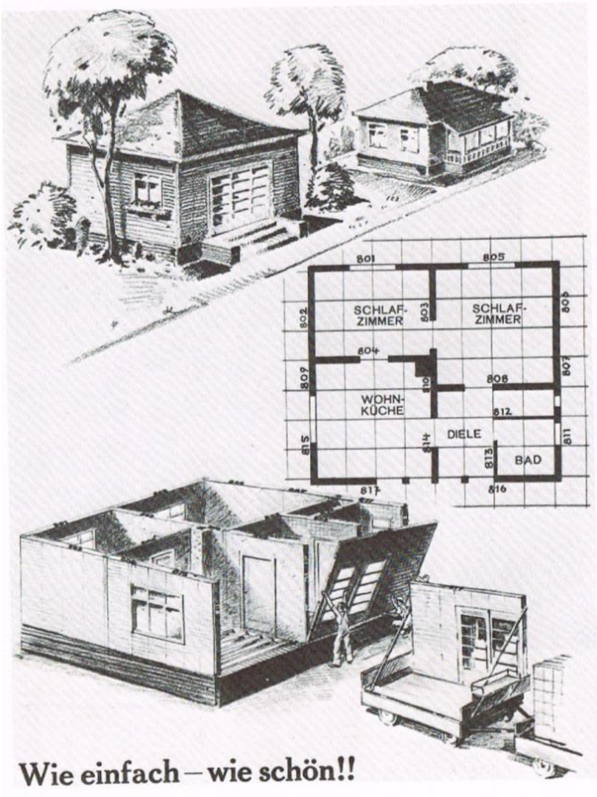


Figure A- 10: Hirsch Kupfer-and Messingwerke, erection procedure, copper house, 1931

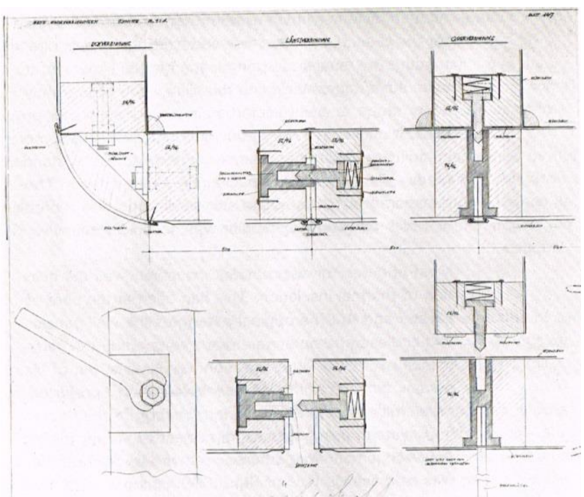
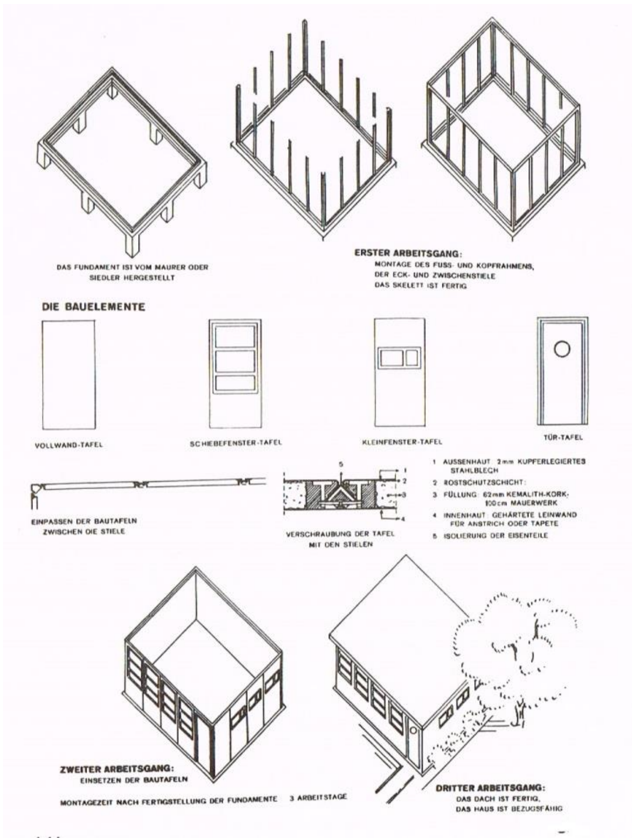


Figure A- 11: Walter Gropius, proposed new connection system for Hirsch panels, 1931-32



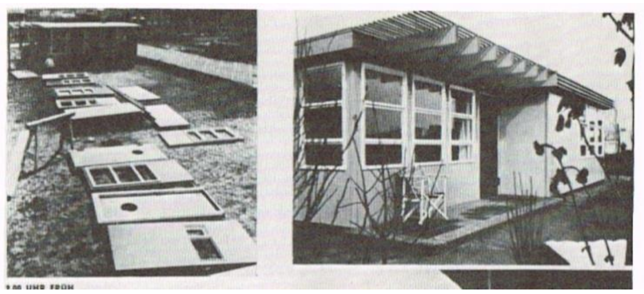


Figure A- 12: Otto Bartning, prefabrication using “Werfthaus System Baetning,” at berlin exhibition, 1932

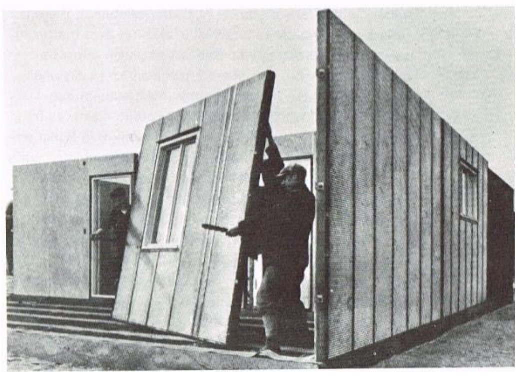


Figure A- 13: Walter Gropius, Grawing House using Hirsch system, Transportation and eriction processes, Berlin exhibition, 1932

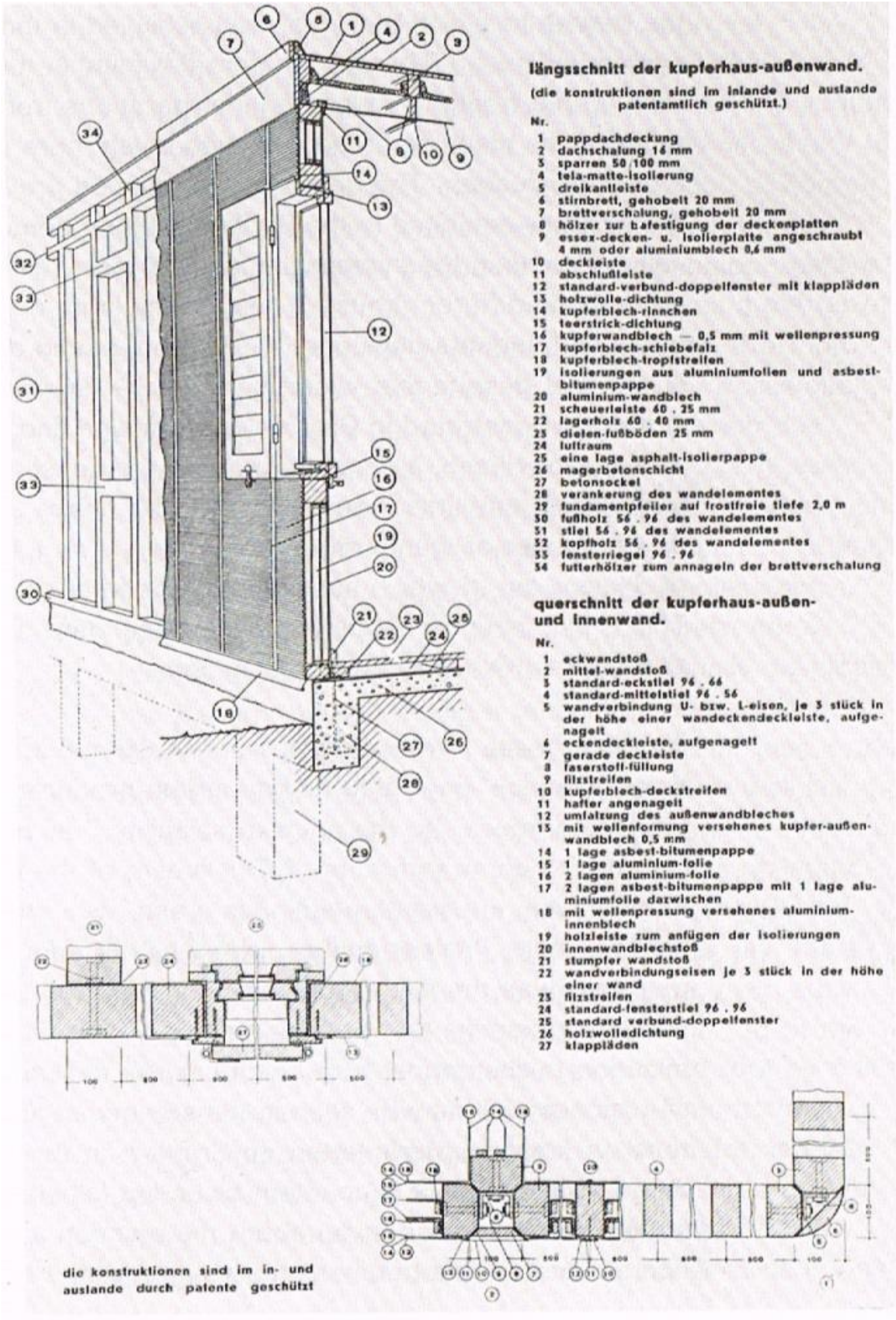


Figure A- 14: Walter Gropius, Growing House using Hrich system, showing revised construction details, Berlin exhibition, 1932

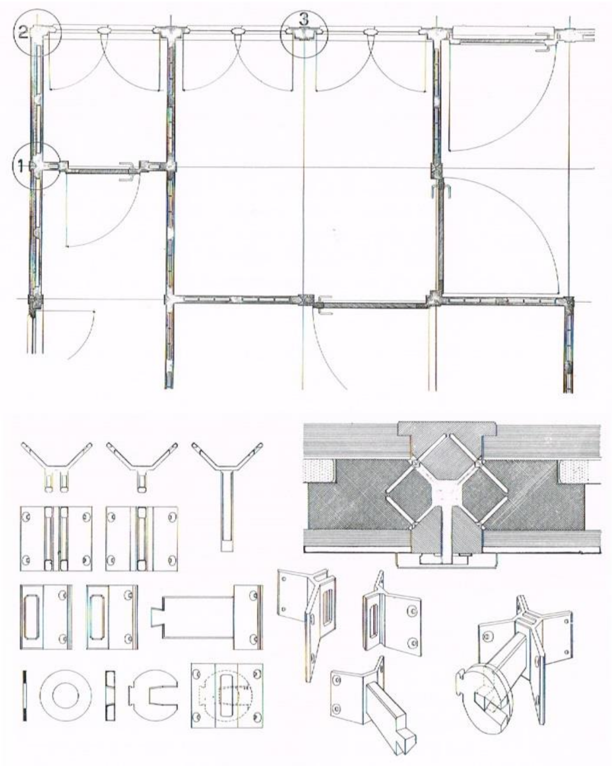


Figure A- 15: Konrad Wachsmann, prefab system (French scheme), combination of panels and metal connectors, c. 1939

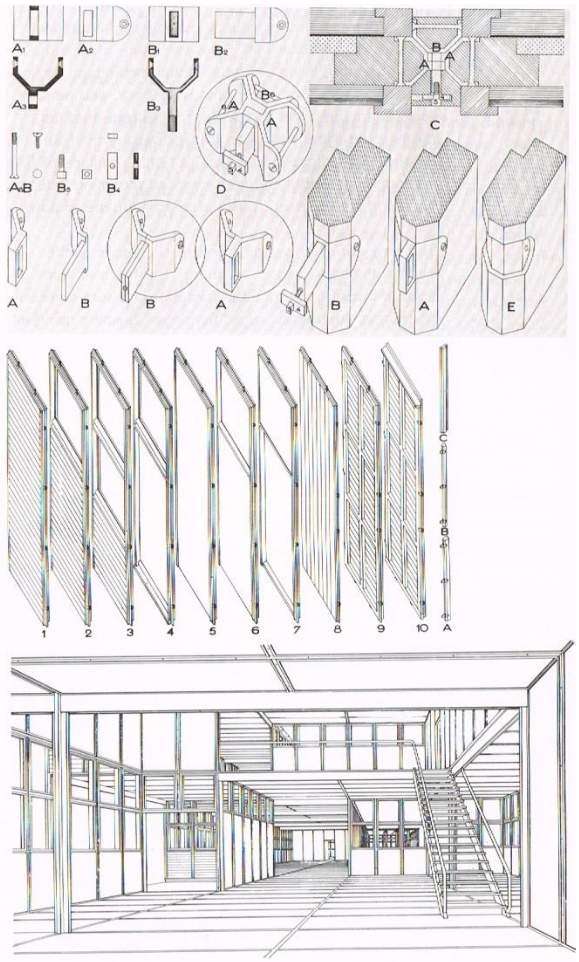


Figure A- 16: Konrad Wachsmann, modified cheme, detail of metal connector, panels and sectional perspective 1941

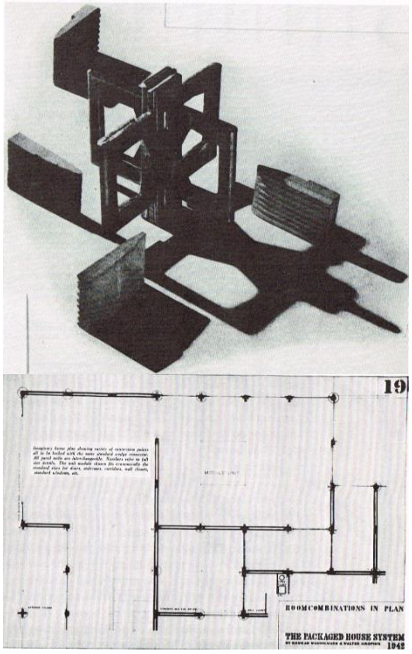


Figure A- 17: Wachsmann and Gropius, Packaged House, wedge connector, and packaged House system, 1942

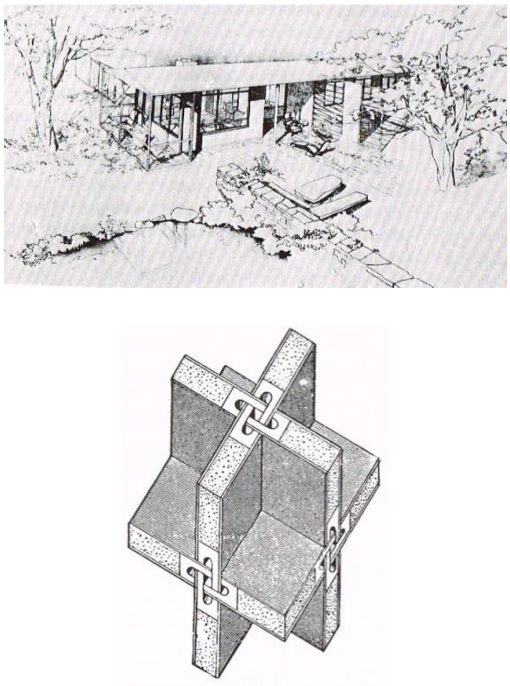


Figure A- 18: Walter Gropius, expansible house using General panel components, 1944

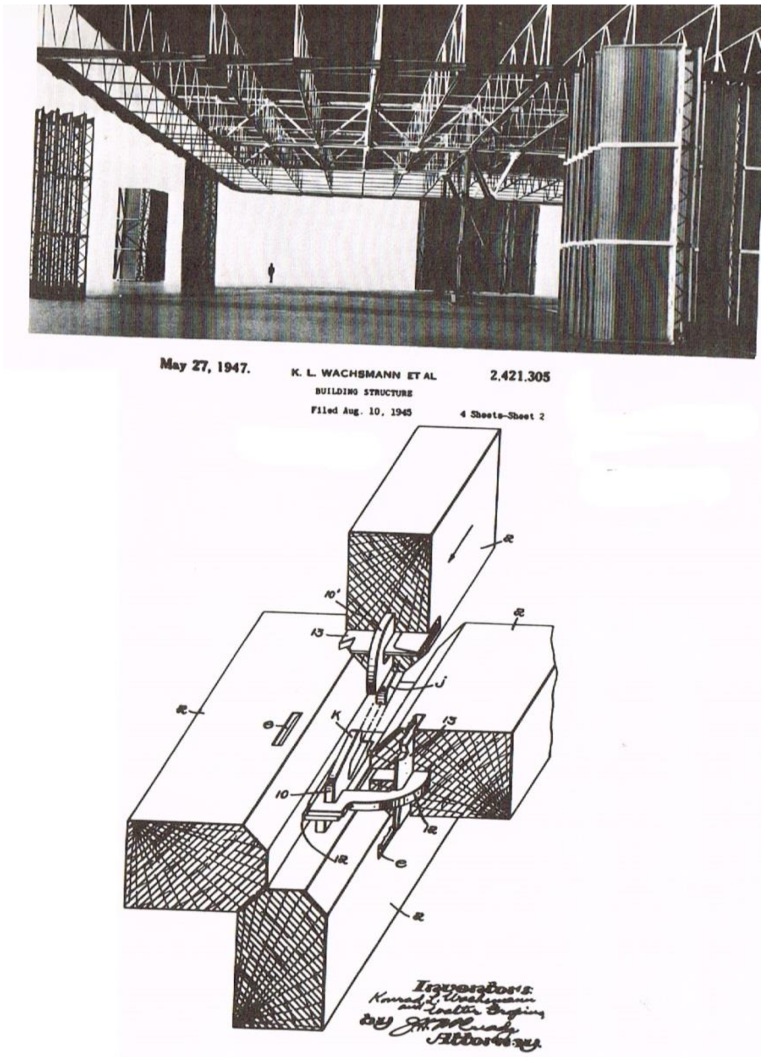


Figure A- 19: Top, Konrad Wachsmann Mobilar hanger system, 1939-45, bottom, Wachsmann et al., building structure (U.S. patent application), 1945

Appendix 10: Precast elements production

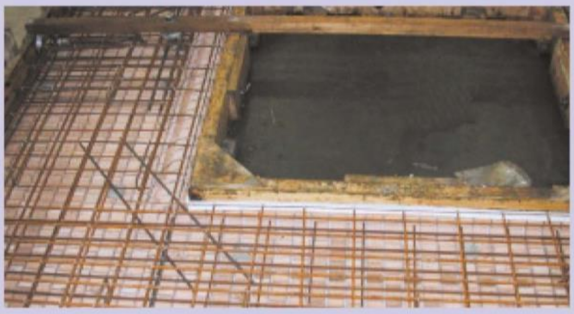
Steps of precast elements production

Precast units are detailed in the drawing office

Stone facings are positioned face-down in the base of the mould

A timber mould under construction

The bending of steel reinforcement has been automated



The reinforcement is laid in the mould

Stainless steel fixings are fabricated for cladding components

The mix is poured into the mould...

After casting, precast units are craned into the yard

and vibrated to fully compact the concrete

A mock- up unit is propped in the yard

Figure A- 20: Production process of precast elements

Appendix 11: Types and capacity of cranes

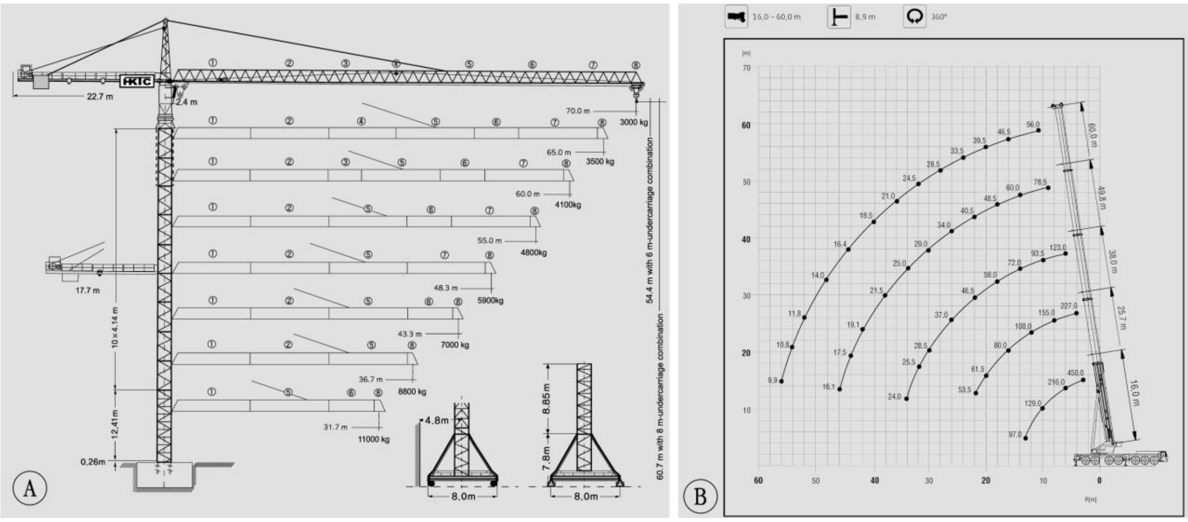


Figure A- 21: (A) Tower Crane Dimensions and load capacity limits. (B) Mobile Crane Dimensions and load capacity limits (A) (Cranewale), (B) (CHALUPA , 2013)

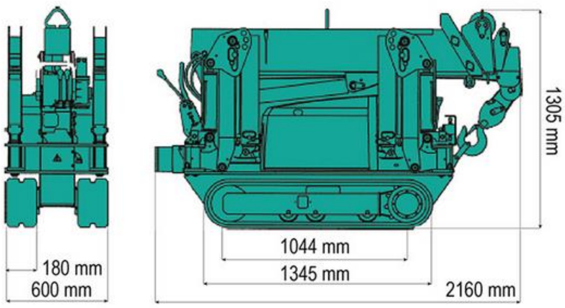
Mini Cranes

Small or mini cranes that can be used inside the building for installation of relatively heavy equipment and component can be found in a wide range in the machine market. The following is a sample of such machines (Uplifter, 2017).

Mini Crane Maeda MC 104

The smallest Maeda Mini Crane manufactured by Uplifter Machine Company in Germany whit excellent load bearing capacity (see the following specifications).

- 0.995 Ton Max capacity
- 5.5 m Max Working Height
- Slim Body (600 mm)
- Electric Motor
- Low Ground Pressure
- Maneuverability & Stability
- Hydrostatic Transmission
- Remote Control



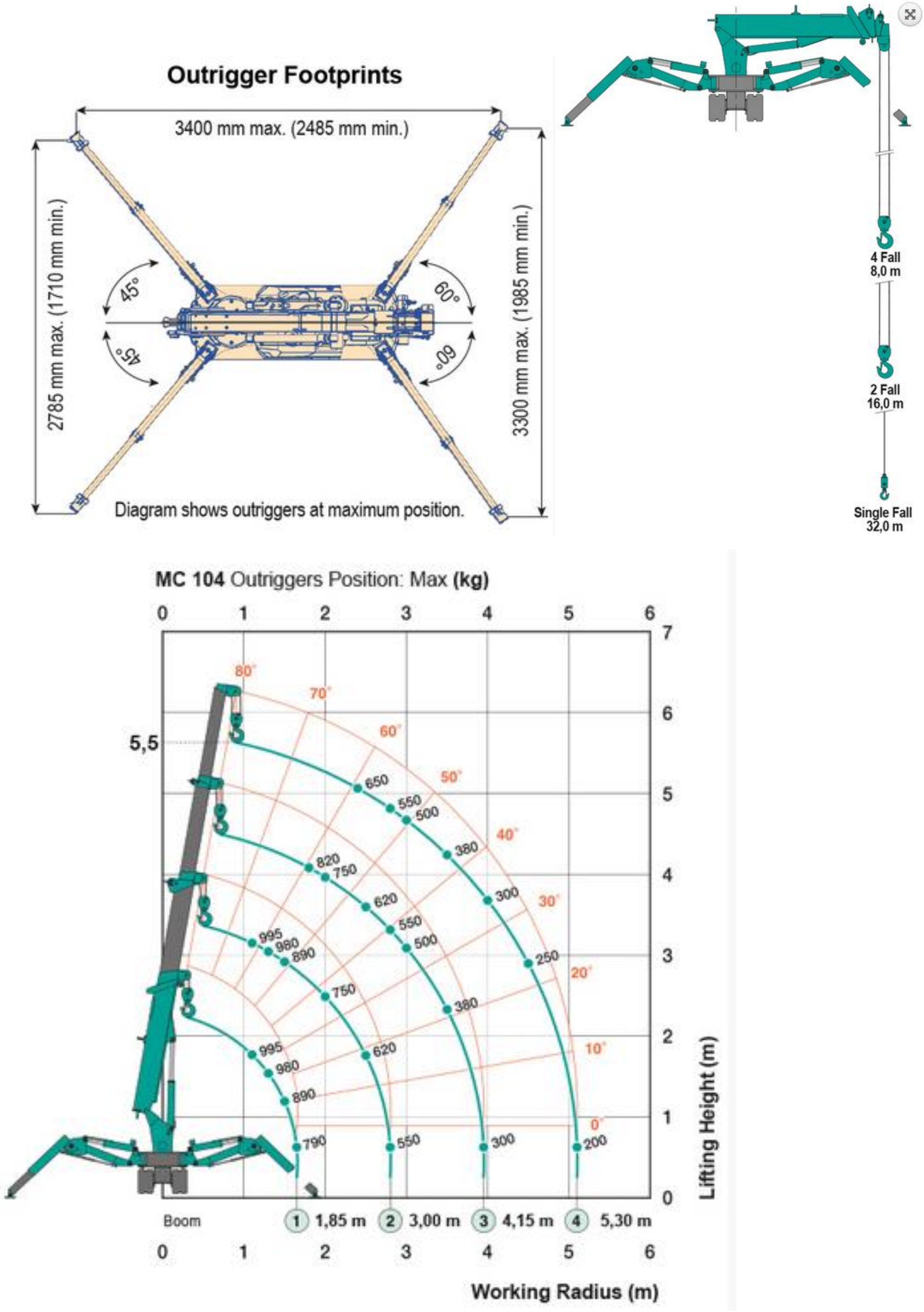


Figure A- 22: Sample mini Crane specifications

Appendix 12: Installation of precast elements

The following procedure shows the conventional installation methods and fixing by cement mortar for conventional elements. The installation method for demountable proposed system will not include grouting and the use of permanent connections. However, the procedures still the same regarding installation.

Vertical component installation

Installation sequence	Good practices
1. Setting out	

1.1. Set reference line and offset line to determine the position of the precast elements to be installed.

1.2. Provide level pads (or shim plates) for setting the level of the elements. Set the level pads in position using non-shrink mortar.

1.3. For precast external wall/ column, fix the compressible form or backer rod on the outer perimeters of wall.

- Check the accuracy of the offset lines.
- Check the shim plate level and stability.
- For vertical precast component, check the positions and alignment of the starter bars before hoisting for installation.

- Check that the compressible form or backer rod are properly secured.

Installation sequence	Good practices
2. Lifting and installation	

2.1. Lift and rig the panel to its designated location with the use of wire ropes.

2.2. Adjust the panel to position and secure it with diagonal props.

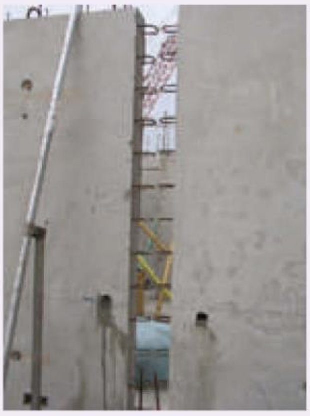
- Check the hoisting condition of the precast element.
- Check alignment and verticality of the panel. If necessary, adjust the temporary propping to achieve the level and position of the precast element.

- Check the stability of the erected props before releasing the hoisting cable.

Installation sequence	Good practices
3. Grouting work	
3.1. Prepare and apply non-shrink mortar to seal the gaps along the bottom edge of the inner side of the panel. 	• Check that the joint width between panels are within design allowances before grouting. 
3.2. For corrugated pipe sleeve or splice sleeve connection, prepare and pour non-shrink grout or proprietary grout into the pipe inlets provided. 	• Non-shrink grout used at the interface with the precast elements should preferably be free flowing and self compacting in nature so as to ensure good compaction at the joint and to minimise the risk of cracking. • Non-shrink grout should be prepared in accordance with the specifications. 
3.3. Keep the installed panels undisturbed for at least 24 hours.	• Check that all horizontal joints are properly sealed. • Collect sample test cubes of the grout mix used for critical elements such loading bearing walls for testing.

Installation sequence	Good practices
4. Joint casting and sealing	

4.1. For panels with cast in-situ joints, install the joint rebars as required.

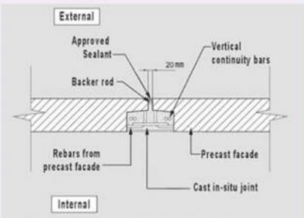


4.2. Set up forms for the casting of the vertical joint.

4.3. Carry out concrete casting.

4.4. Remove forms after sufficient concrete strength has been achieved.

4.5. For joints between façade walls or between external columns with beams or walls elements, approved sealant and grout will be installed at later stage.



Example of vertical joint details between precast façade panels

4.6. For panel with welded connection, place the connecting plate between the panels and carry out welding as per design requirement.

- The joint rebars should be correctly placed in accordance with the design specifications.
- The formwork should be properly secured during the casting operation of the joint.

- The joint gaps should be consistent to allow for proper installation of sealant or grout for better watertightness.

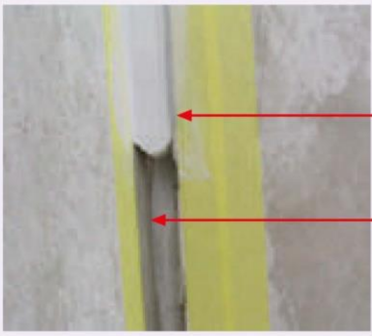


Figure A- 23: Installation of vertical precast elements

Horizontal component installation

Installation sequence	Good practices
1. Setting out	
1.1. Set reference line and offset line to determine the required alignment and level of the precast slab/beam elements during installation.  	• Check the accuracy of the offset lines. • Check the level and stability of the shim plates. • Before hoisting, check that the dimensions and alignment of the protruding bars are within the specified tolerance, to prevent any obstruction during the erection process. 
2. Lifting and installation	
2.1. Put up temporary props to support the precast slab/beam elements. 	• Beam elements should be supported at minimum two locations during hoisting. 

Installation sequence	Good practices
2. Lifting and installation (cont'd)	
2.2. Lift and rig the elements to designated location with the use of wire ropes. 	• Balcony, planter ledge and slab should be supported at more than two locations, depending on the dimensions of the elements and design consideration. 
2.3. Align and check level to suit the required setting out before placement of precast members to final position.  	• It is important to check on the levelness of the precast elements as well as between the elements before proceeding to do the jointing works. 

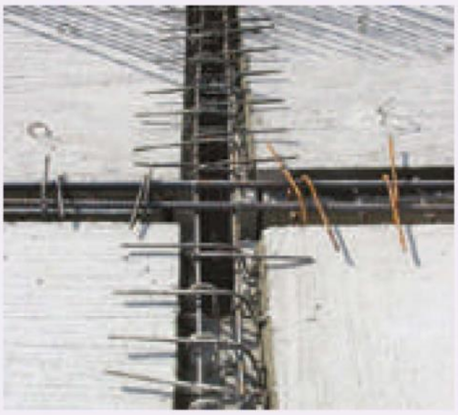
Installation sequence	Good practices
3. Casting of joints	
3.1. For components with cast in-situ joints, place and lap the rebars as required.  3.2. Set up the formwork for the casting of the joint.  3.3. Carry out concrete casting. 3.4. Remove forms after sufficient concrete strength has been achieved. 	• The joint rebars should be correctly placed in accordance with the design specifications.  • The formwork should be properly secured during casting of the in-situ joint. • Supporting beams can be designed to form part of the formwork for the casting of joint.  

Figure A- 24: Installation of horizontal precast elements

Rigging

A rigging system for handling and erecting precast elements requires careful and thorough pre-planning. Special care must be taken with rigging arrangements where unequal insert loading has been incorporated in the panel design.

It may be necessary to equalise loads between lifting points on certain precast elements, such as beams or flat slabs. Particular care should be taken to determine when this is necessary.

Lifting accessories may be in the form of slings/cables, hooks or shackles. The selection of such components should take into consideration the forces due to all operations involved in the handling and erection of the precast units. Headroom availability and manoeuvrability during erection may also have an impact on the type of rigging system selected.

Refer to the Figure for some common rigging configurations.

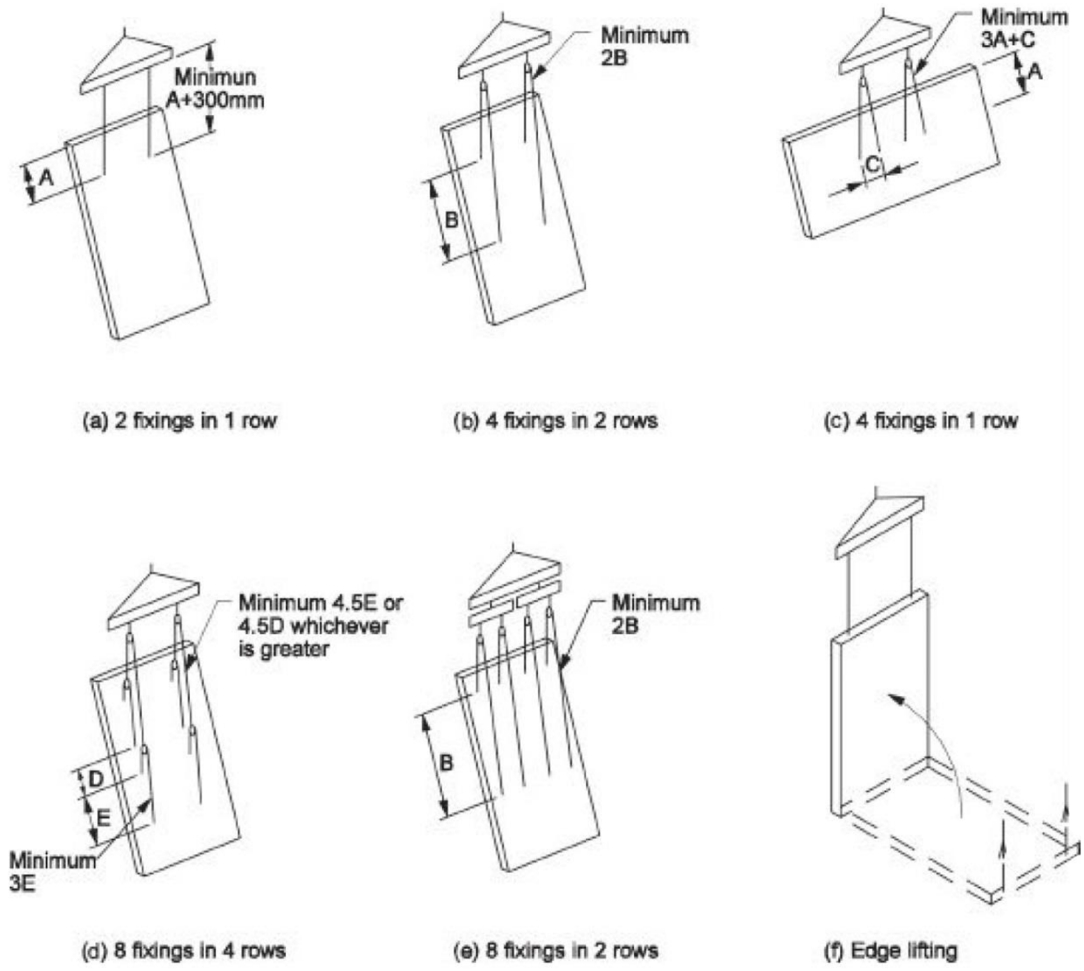


Figure A- 25: Rigging configurations for handling and erecting precast panels (Pang, et al., 2003)

Appendix 13: Evaluation of common precast structural elements

DfD aspects and their sub-aspects and their values for various precast concrete structural systems based on the model of Durmisevic

Number	*DfD aspect*	*(D.F.) Abbreviation*	*D.F. type*	foundation with holding down bolts	*D.F. type*	Pocket foundation	*D.F. type*	columns with concrete corbels and fixing bolts	*D.F. type*	Structural walls	*D.F. type*	Beams with fixing steel plates	*D.F. type*	Beams with fixing holes	*D.F. type*	Hollow core slabs	*D.F. type*	Double-T slabs
1	FD (Functional decomposition	fs	fs 01	1	fs 01	1	fs 01	1	fs 01	1	fs 01	1	fs 01	1	fs 01	1	fs 01	1
		fdp	fdp 01	1	fdp 01	1	fdp 01	1	fdp 01	1	fdp 0	1	fdp 0	1	fdp 0	1	fdp 0	1
	Result			**1**		**1**		**1**		**1**		**1**		**1**		**1**		**1**
2	SY (Systematization) [1]	st	st 03	0.6	st 03	0.6	st 03	0.6	st 03	0.6	st 03	0.6	st 03	0.6	st 03	0.6	st 03	0.6
		c	c 01	1	c 01	1	c 01	1	c 01	1	c 01	1	c 01	1	c 01	1	c 01	1
	Result			**0.80**		**0.80**		**0.80**		**0.80**		**0.80**		**0.80**		**0.8**		**0.8**
3	BE (Base element)	b	b 01	1	b 04	0.1	b 02	0.6	b 04	0.1	b 01	1	b 01	1	b 04	0.1	b 04	0.1
	Result			**1**		**0.1**		**0.6**		**0.1**		**1**		**1**		**0.1**		**0.1**
4	LCC (Life cycle coordination)	ucl	ucl 01	1	ucl 01	1	ulc 01	1	ulc 01	1	ucl 01	1	ucl 01	1	ucl 01	1	ucl 01	1
		tcl	tcl 01	1	tcl 01	1	tcl 01	1	tcl 01	1	tcl 01	1	tcl 01	1	tcl 01	1	tcl 01	1
		s	s 02	1	s 02	1	s 01	1	s 01	1	s 01	1	s 01	1	s 01	1	s 01	1
	Result			**1**		**1**		**1**		**1**		**1**		**1**		**1**		**1**
5	RP (Relational pattern)	r	r 01	1	r 01	1	r 01	1	r 01	1	r 01	1	r 01	1	r 01	1	r 01	1
	Result			**1**		**1**		**1**		**1**		**1**		**1**		**1**		**1**
6	A (Assembly process)	ad	ad 04	0.1	ad 04	0.1	ad 04	0.1	ad 04	0.1	r 04	0.1	r 04	0.1	r 04	0.1	r 04	0.1
		as	ad 04	0.5	ad 05	0.3	as 04	0.5	as 04	0.5	as 04	0.5	as 04	0.5	as 04	0.5	as 04	0.5
	Result			**0.3**		**0.2**		**0.30**		**0.30**		**0.30**		**0.30**		**0.3**		**0.3**
7	G (Geometry)	gp	gp 05	0.2	gp 05	0.2	gp 06	0.1	gp 01	1	gp 06	0.1	gp 02	0.8	gp 02	0.8	gp 02	0.8
		spe	spe 01	1	spe 01	1	spe 01	1	spe 01	1	spe 01	1	spe 01	1	spe 01	1	spe 01	1
	Result			**0.6**		**0.6**		**0.55**		**1**		**0.55**		**0.90**		**0.9**		**0.9**
8	C (Connection)	tc	tc 02	0.8	tc 07	0.2	tc 03	0.6	tc 03	0.2	tc 03	0.6	tc 03	0.8	tc 07	0.2	tc 07	0.2
		af	af 05	0.1	af 05	0.1	af 04	0.4	af 05	0.1	af 04	0.4	af 04	0.4	af 05	0.1	af 05	0.1
		tc	t 01	1	t 01	1	t 02	0.5	t 02	1	t 03	1	t 03	1	t 02	1	t 02	1
		mj	mj 03	0.6	mj 03	0.6	mj 04	0.1	mj 04	0.1	mj 04	0.1	mj 03	0.6	mj 04	0.1	mj 04	0.1
	Result			**0.63**		**0.48**		**0.52**		**0.35**		**0.42**		**0.60**		**0.35**		**0.35**
Disassembly potential				**0.79**		**0.65**		**0.74**		**0.89**		**0.77**		**0.84**		**0.70**		**0.70**

[1] : Regarding systematization in the structure functional level of the building the load bearing elements have been given the value of 0.6 as mentioned in the model of Durmisevic however, this value is the highest value that could be given since load bearing element in this context do not exist as components.

Appendix 14: Evaluation of common precast infill elements

DfD aspects and their sub-aspects and their values for Different precast concrete infill systems based on the model of Durmisevic

	DfD aspect	*(D.F.) Abbreviation*	*D.F. type*	lightweight partition panels	*D.F. type*	Thin concrete slabs with precast studs	*D.F. type*	Precast stairs
1	FD (Functional decomposition	fs	fs 03	0.1	fs 01	1	fs 01	0.6
		fdp	fdp 02	0.8	fdp 02	0.8	fdp 03	0.4
	Result			**0.45**		**0.90**		**0.50**
2	SY (Systematization)	st	st 03	0.6	st 01	1	st 05	0.2
		c	c 04	0.1	c 03	0.3	c 03	0.3
	Result			**0.35**		**0.65**		**0.25**
3	BE (Base element)	b	b 04	0.1	b 02	0.6	b 03	0.3
	Result			**0.1**		**0.60**		**0.3**
4	LCC (Life cycle coordination)	ucl	ucl 01	1	ucl 01	1	ucl 01	1
		tcl	tcl 01	1	tcl 01	1	tcl 01	1
		s	s 02	1	s 01	1	s 02	1
	Result			**1**		**1.00**		**1.0**
5	RP (Relational pattern)	r	r 01	1	r 01	1	r 01	1
	Result			**1**		**1.00**		**1.0**
6	A (Assembly process)	ad	ad 02	0.6	ad 03	0.4	ad 04	0.4
		as	as 07	0.1	as 06	0.5	as 04	0.5
	Result			**0.35**		**0.45**		**0.45**
7	G (Geometry)	gp	gp 06	0.1	gp 01	1	gp 06	0.8
		spe	spe 01	1	spe 01	1	spe 01	1
	Result			**0.55**		**1.00**		**0.90**
8	C (Connection)	tc	tc 07	0.2	tc 01	1	tc 07	0.2
		af	af 05	0.1	af 03	0.6	af 05	0.1
		tc	t 02	1	t 02	1	t 02	1
		mj	mj 04	0.1	mj 04	0.6	mj 04	0.1
	Result			**0.35**		**0.8**		**0.35**
Disassembly potential				**0.51**		**0.80**		**0.61**

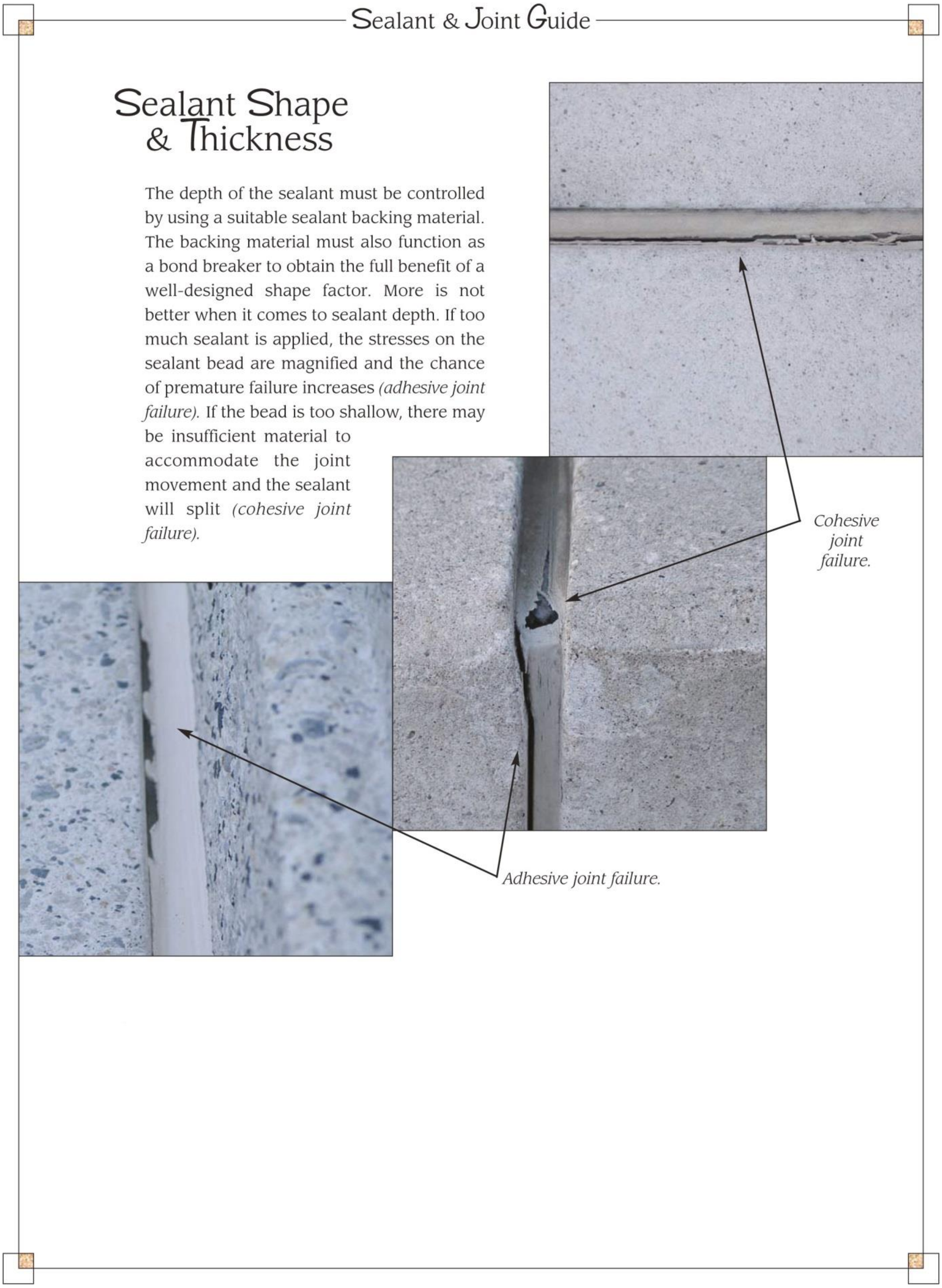
Appendix 15: Jointing materials, Life expectancy and possible problems

Table A- 1: Classification of sealants, sealing strips, gaskets and baffles and their life expectancy (Pang, et al., 2003)

Seal type	Chemical type	Physical type	Movement accommodation (see note 1)	Life expectancy (years) (see note 2)
Gun-applied, non-curing sealants	butyl acrylic	plastic plastoelastic	low low-medium	up to 10 (not exposed) up to 15
Gun-applied, one-part chemically-curing sealants	polysulfide polyurethane silicone	elastoplastic elastic elastic	medium-high medium-high medium-high	up to 25 up to 20 up to 25
Gun-applied, two-part chemically-curing sealants	polysulfide polyurethane silicone	elastoplastic elastic elastic	medium-high medium-high low-high	up to 25 up to 20 up to 25
Sealing strip (mastic)	butyl polyisobutylene/ butyl	plastic elastoplastic	low low	up to 15 up to 15
Sealing strip (cellular)	PVC polyethylene polyurethane butyl neoprene EVA	range in properties from plastic to elastic	low-high	up to 20
Gaskets	neoprene natural rubber EPDM butyl rubber polyurethane silicone EVA	elastic	low-high	up to 20
Baffles	neoprene PVC polyethylene aluminium stainless steel zinc copper	profiles loosely fitted with adjoining components	low-high	up to 40

Notes:

1. The movement that a sealant is capable of tolerating throughout its working life. Expressed as a percentage of the joint width, Low ≈ 5%, Medium ≈ 15%, High ≈ 25%
2. The actual service life of a sealant is dependent not only on composition but also on environmental conditions and quality of application



Sealant & Joint Guide

Sealant Shape & Thickness

The depth of the sealant must be controlled by using a suitable sealant backing material. The backing material must also function as a bond breaker to obtain the full benefit of a well-designed shape factor. More is not better when it comes to sealant depth. If too much sealant is applied, the stresses on the sealant bead are magnified and the chance of premature failure increases *(adhesive joint failure)*. If the bead is too shallow, there may be insufficient material to accommodate the joint movement and the sealant will split *(cohesive joint failure)*.

Figure A- 26: Cohesive and adhesive failures of joints and their reasons (CPCI, 2006)

Sealant & Joint Guide

The Most Common Problems with Existing Procedures

Bond

- Panels manufactured early in the year (January, February, March) are erected and caulked while concrete is still 'green'.
- Precast joints surfaces may not be properly dried or contain frost at time of sealant installation.

Recommendation: **Provide temporary construction joint and install sealants in warmer weather.**

Sealant Cracking / Splitting at Outside Corners

- During late fall and early spring there may be excessive movement at corners before sealant has cured and /or excessive movement due to anchor positions.

Recommendation: **Provide temporary construction joint and install sealants in warmer weather.**

Sealant Failure on Large Spandrels

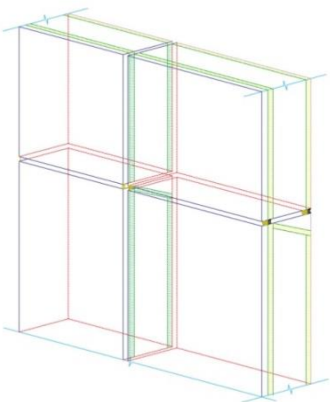
- Excessive movement - sealant is overly compressed and loses memory.

Recommendation: **Increase joints sizes to accommodate expected joint compression.**

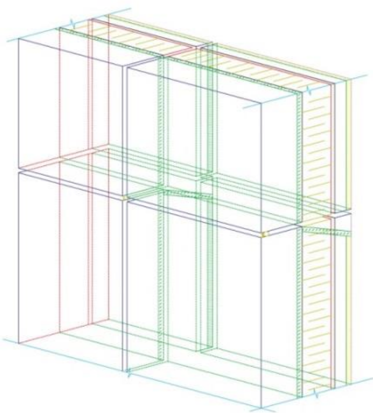
Designing a 3D System in 2D

- Some wall designs handle water properly in two-dimensional blueprints but fail in three-dimensional reality.

Recommendation: **Isometric drawings should be used to show the proper intersection of horizontal and vertical seals and flashings. These intersections are a prime source of water problems. The second line of sealant placed must run continuously across the intersection.**



Isometric of single wythe panel.



Isometric of insulated panel.

Figure A- 27: The most common problems of joints and their solutions (CPCI, 2006)

Appendix 16: Evaluation of common precast façade systems

DfD aspects and their sub-aspects and their values for Different precast façade systems based on the model of Durmisevic

	DfD aspect	*Abbreviation*	*Determining factor (D.F.)*	*D.F. type*	Conventional panels	*D.F. type*	Sandwich panel	*D.F. type*	Fiber reinforced concrete façade
1	FD (Functional decomposition	fs	(Functional separation)	fs 01	1	fs 02	0.6	fs 02	1
		fdp	(Functional dependence)	fdp 02	0.8	fdp 02	0.8	fdp 02	0.8
	Result		………………………………………		**0.90**		**0.70**		**0.90**
2	SY (Systematization	st	Structure and material levels	st 05	0.2	st 05	0.2	st 05	0.2
		c	Clustering	c 04	0.1	c 01	1	c 01	0.1
	Result		…………………………………		**0.15**		**0.60**		**0.15**
3	BE (Base element)	b	Base element specification	b 03	0.3	b 03	0.3	b 03	0.3
	Result		……………………………………		**0.30**		**0.30**		**0.30**
4	LCC (Life cycle coordination)	ucl	Use life cycle coordination	ucl 01	1	ucl 01	1	ucl 01	1
		tcl	Technical life cycle coordination	tcl 01	1	tcl 01	1	tcl 01	1
		s	Coordination of life cycle and size	s 02	1	s 01	1	s 01	1
	Result		……………………………………		**1.00**		**1.00**		**1.00**
5	RP (Relational pattern)	r	Type of relational pattern	r 01	1	r 01	1	r 01	1
	Result		………………………………………		**1.00**		**1.00**		**1.00**
6	A (Assembly process)	ad	Assembly direction	ad 03	0.1	ad 01	1	ad 01	1
		as	Assembly sequence	as 04	0.5	as 07	1	as 04	0.5
	Result		……………………………………		**0.30**		**1.00**		**0.75**
7	G (Geometry)	gp	Geometry of product edge	gp 06	0.1	gp 04	0.4	gp 01	1
		spe	Standardization of product edge	spe 01	1	spe 01	1	spe 01	1
	Result		………………………………………		**0.55**		**0.70**		**1.00**
8	C (Connection)	tc	Type of connection	tc 02	0.8	tc 02	0.8	tc 02	0.8
		af	Accessibility to fixing	af 03	0.6	af 02	0.8	af 02	0.6
		t	Tolerance	t 02	1.0	t 02	1.0	t 02	1.0
		mj	Morphology of joint	mj 04	0.1	mj 04	0.1	mj 04	0.1
	Result		……………………………………		**0.62**		**0.67**		**0.71**
	Disassembly potential		>>>>>>>>>>>>>>>>>>>>>>>>>>>		**0.60**		**0.74**		**0.72**

Appendix 17: Details for the design of the proposed finishing component

Figure A- 28 shows the various component of the demountable exterior finishing component developed mainly for exterior finishing such as stone. Also other materials can also be used with little variation in the design. In this example a simple load bearing steel bin is used and the panel could be fixed from the corners using T-shaped steel bolts that fasten back plates.

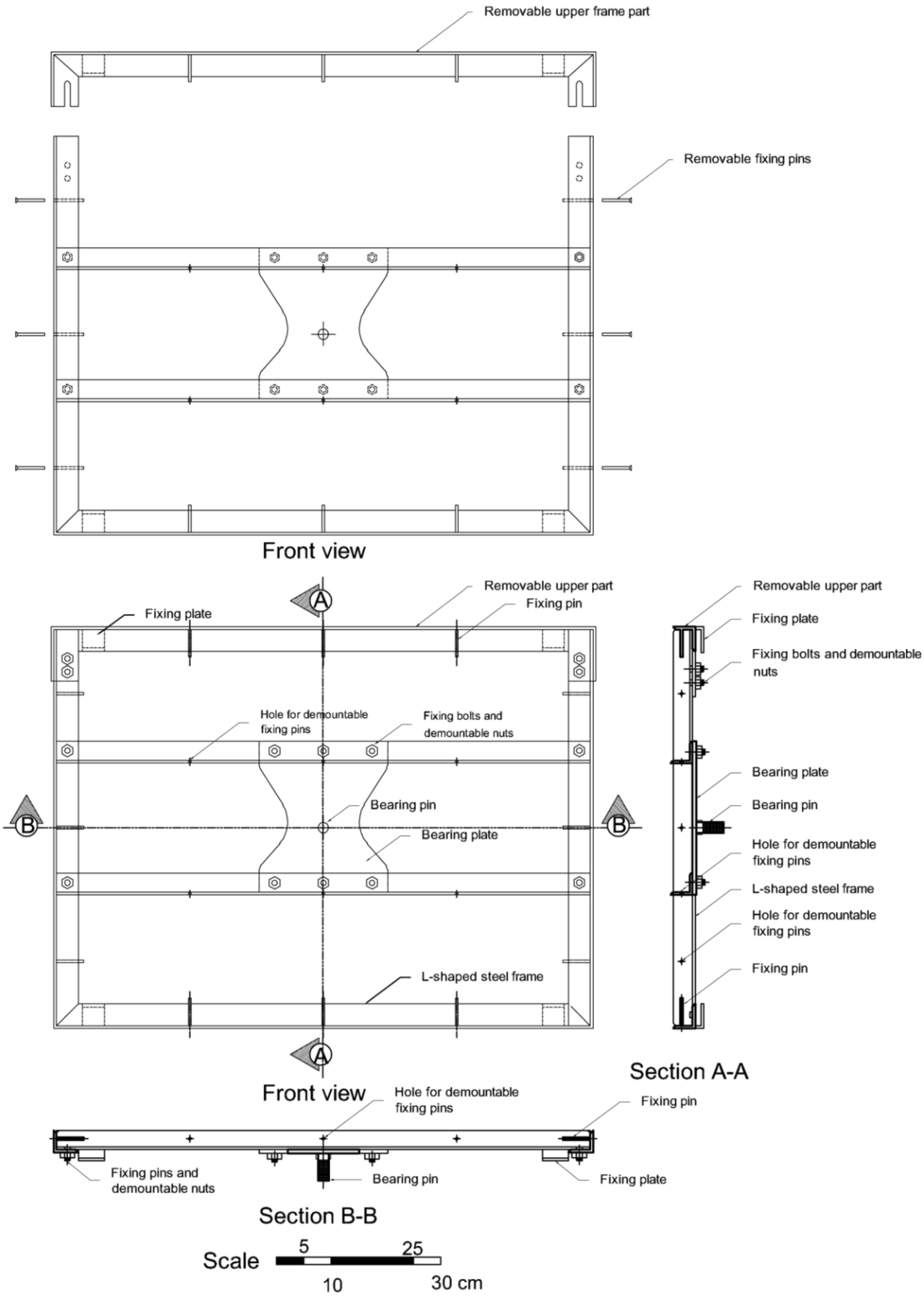


Figure A- 28: The design of finishing component

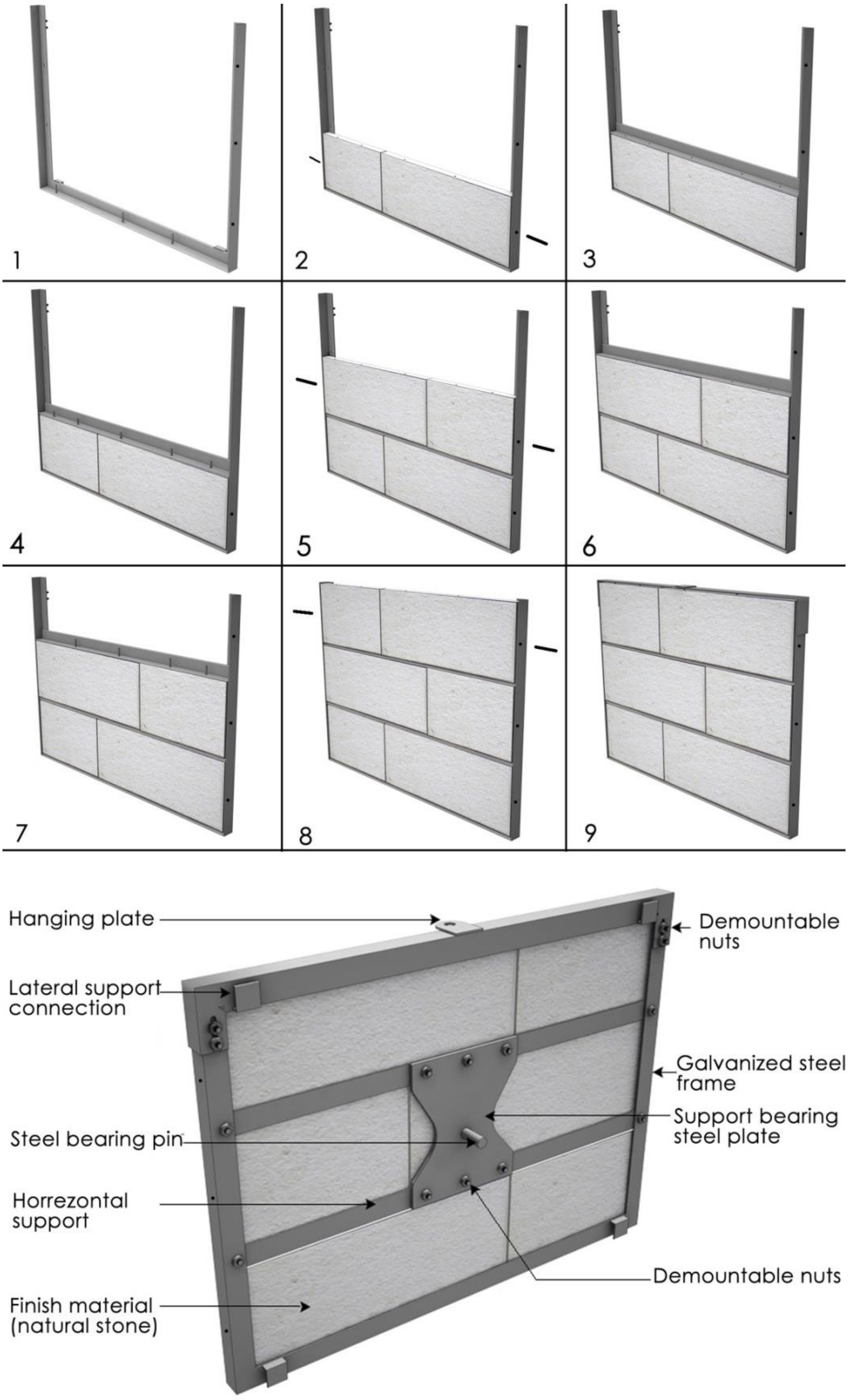


Figure A- 29: Steps of the assembly of the external finishing component

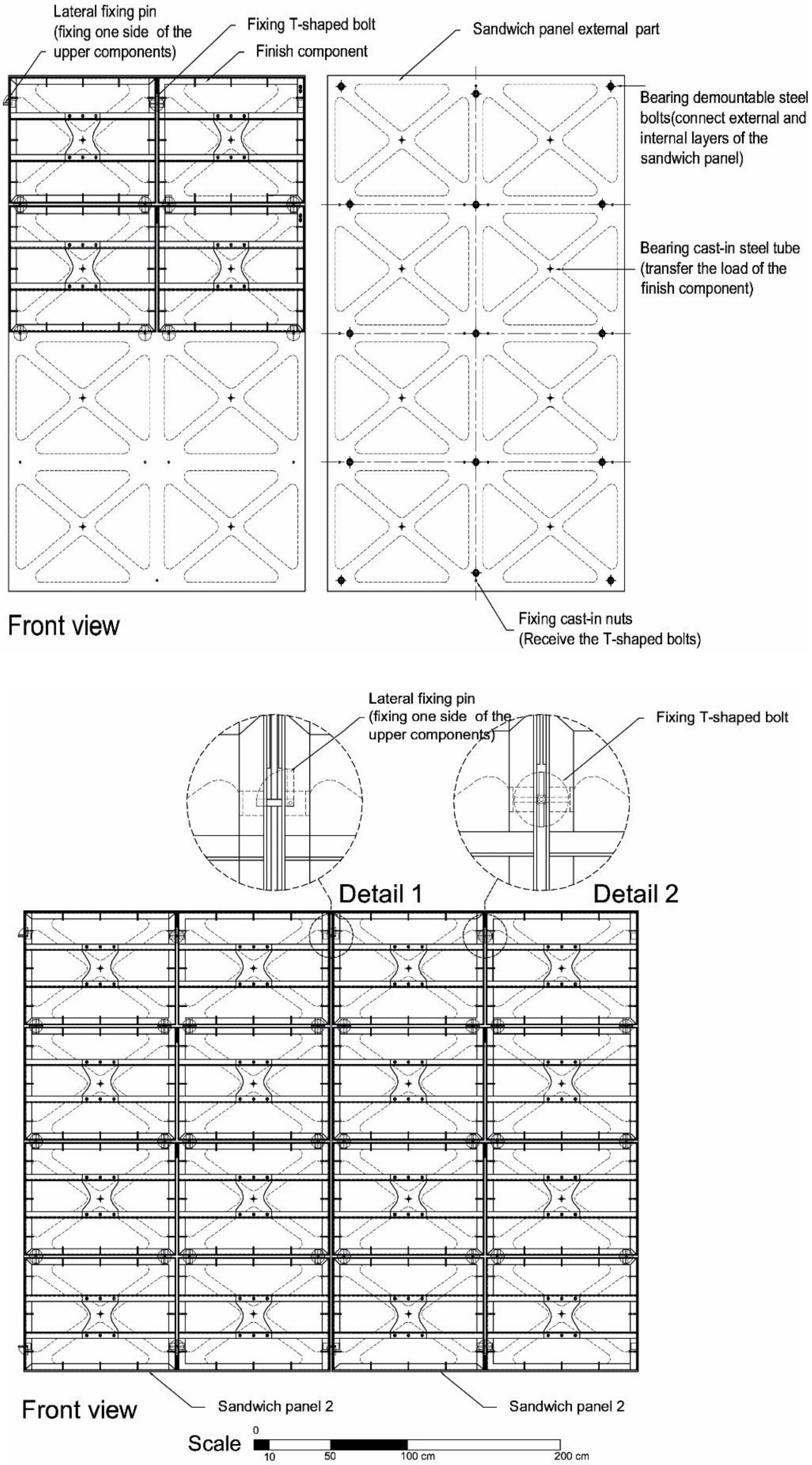


Figure A- 30: Assembly of the finish component (some details have been neglected for clearance).

Figure A- 31 shows details of a proposed demountable mechanical connection that require insert of the load bearing pin and press to fix and mount the exterior component. Then locking parts at the corner of the component can be used to lock the component and prevent from movement. The disassembly of the component from the façade panel requires unlocking the corner parts and pressing again then pull. The grooved load bearing pin in the external component is inserted to a rotational jagged edge cylindrical tube that is interlocked into an integrated counter jagged part in the exterior component. his part is connected to a rotational cylindrical tube with fastening plates. The fastening plates are inserted to the cast-in-panel part through longitudinal openings. Then rotated by the transferring the axial linear movement of bin insert to rotational movement that cause the fastening plates to rotate 90 degrees. At that degree these plates are pushed through the under plate to a rectangular hole that fix the plates and stop its rotation. Lock parts near the component corners are then used to prevent from further movement of the component towards the facade panels resulting on a fixed state. To disassemble the exterior component from the facade panels, rotation of the locking parts near the corner allow movement through press towards the façade panels. That release the intersecting parts of the fastening plates and generates another 90 degrees rotation that return the fastening plates to the initial position. This allow the panel to be disassembled through pull action.

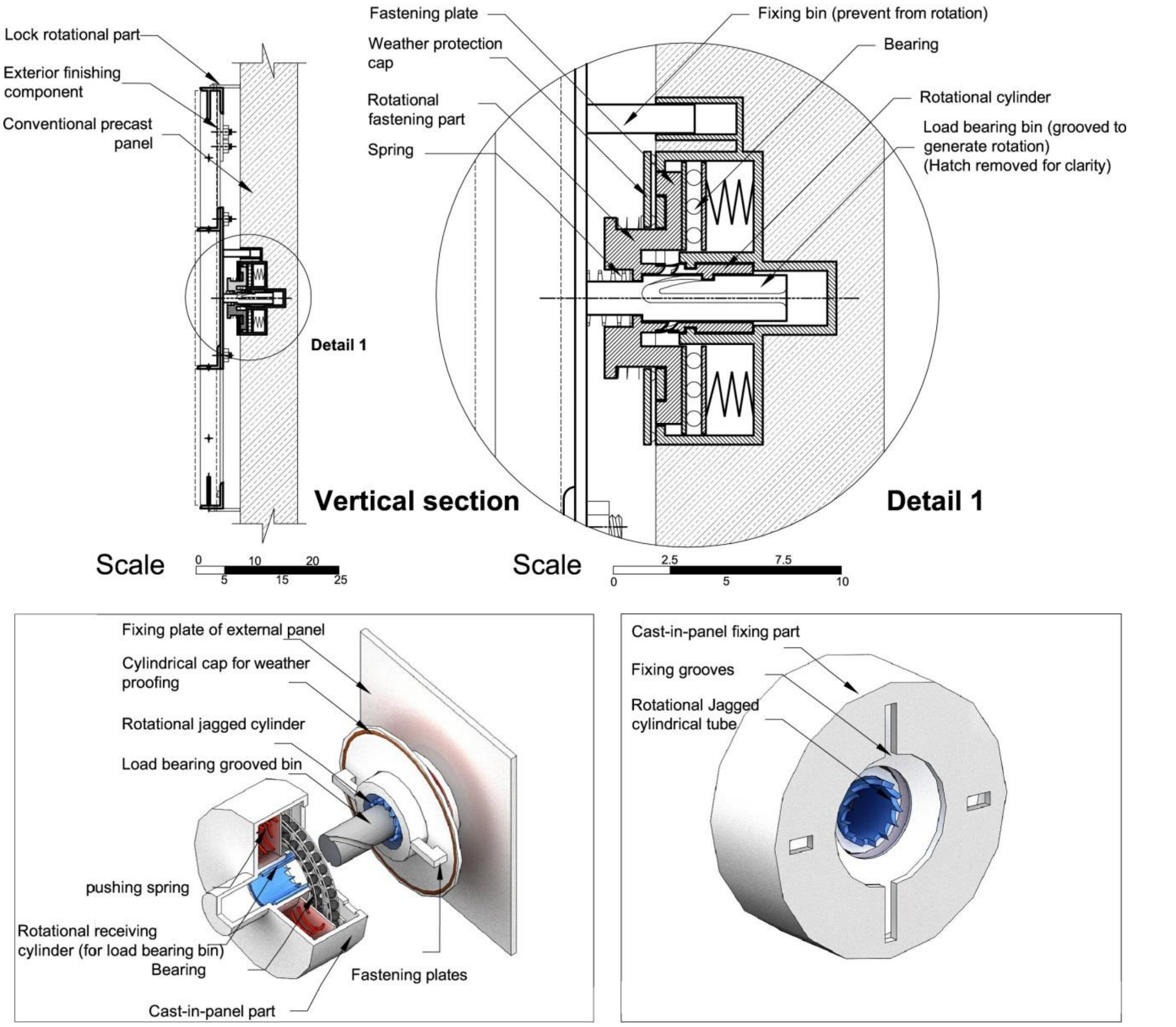


Figure A- 31: Demountable mechanical connection, insert and press to mount/ press and pull to demount

Other options for demountable external finishing component are indicated in figure a- 32. Two options are proposed. The first by using magnate with adequate pull force as lower connector, and the other is by using snap fastener also with adequate fixing strength. Both of the two options are based on fixing upper steel that interlocked with a hanging plate with special hole. In this case a suitable space is left between the finishing components in the vertical direction.

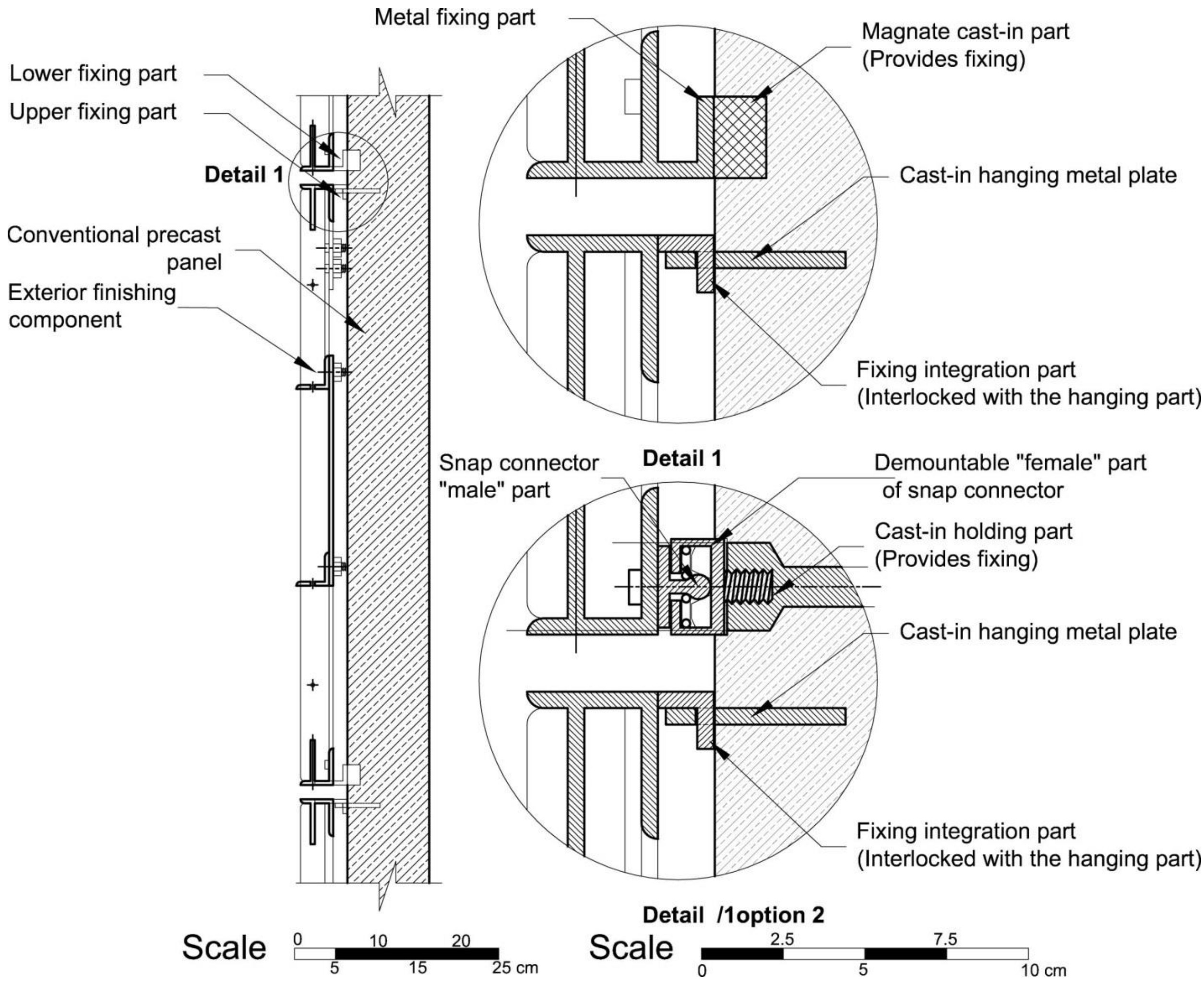


Figure A- 32: Proposed demountable connections for the external finishing component

Appendix 18: Design strategy and recovery options for precast systems

1. Recovery of the system and the applied design strategy

To guarantee a high transformation capacity of the system, and the possibility for reuse, the main design strategy included considering independence and exchangeability of the system and its parts. Such strategy guarantees the possibility to extract every element or material separately for reuse or recycle. Other design strategies such as accessibility to the connections and services and the replaceability of parts also have been applied to raise the value of the system. In addition to that, systematization of the structural and material levels as well as clustering of them where design strategies toward fast assembly and disassembly. This strategy makes the reuse of each component separately possible. Standardization of edges was also a design strategy that supports the reuse potential of the system and its parts through increasing the compatibility between elements and their reuse options. The table below shows how the design strategy affects various recovery options of the system and its parts.

Table A- 2: Reflection of the design strategies of the system on various recovery options

No./Title	Design strategy	Recovery option
1	Independence and exchangeability	-Reuse of the system -Reuse of the system parts -Recycle of materials/down cycle of elements
2	Systematization	-Reuse of components separately
3	Accessibility	-Reuse of the system -Reuse of the system parts -Recycle of materials
4	Replace-ability	-Reuse of the system -Reuse of the system parts
5	Standardization of edges	-Reuse of the system -Reuse of the system parts

1.1. Recovery options

At the end of the system function, the system is disassembled and a sorting process that categorizes elements into different categories begins. The sorting process guarantees a suitable recovery option for the system and its parts. When the system is classified as reusable due to a good quality, a suitable reuse option can be then applied.

Some parts may need refurbishment and maintenance to be reusable. After applying the refurbishment process the system parts could be reused after they pass quality control tests. Any parts that cannot be reused or preserved should be fed back to the life cycle by recycling or down cycling.

The development that has been applied to the previously discussed façade systems provides the possibility to reuse either the system as a whole or its parts as follows:

1.1.1.Recovery of the whole system

The priority is for the reuse of the system as a whole which provides the maximum reuse potential of elements and materials. The most suitable option for the reuse of the whole system is to be used for the same purpose that it has been designed for. This option will make use of the full functionalities of the system including thermal insulation, separation, and appearance. In addition to the use for facades, the facade panels could be used for flat or pitched roofs nevertheless; some additional details might be required mainly for protection from water penetration. Other reuse options are possible such as the use of panels as slab on grade, but also, in this case, some additional details might be required. It is important to mention that the most important aspects that have been provided to the system to ensure its suitability to different designs are the geometry of element edge and the type of connection.

1.1.2.Recovery of the system parts

In case there were obstacles to the reuse of the whole system, its parts and elements could be recovered by one of the recovery options: reuse, recycle or down cycle respectively. The reuse options for the parts of the system are various and multiple.

2. Recovery of the sandwich panel parts.

Starting with the concrete wythes which can be reused separately another time in building facades. For example, the interior wythe is ready to be used as a conventional panel. The exterior wythe also could be used for building facades, however, some details mainly for connections need to be considered. The insulation material could be reused when it preserves its quality or could be recycled for the production of new insulation materials. The exterior finish component could be dismantled to its elements and materials level. The steel frame could be reused or recycled and the finishing material also could be reused in case of metal, stone or wood, never the less some refurbishment could be required. Figure A- 33 shows some proposed value proposition for the parts of the system.

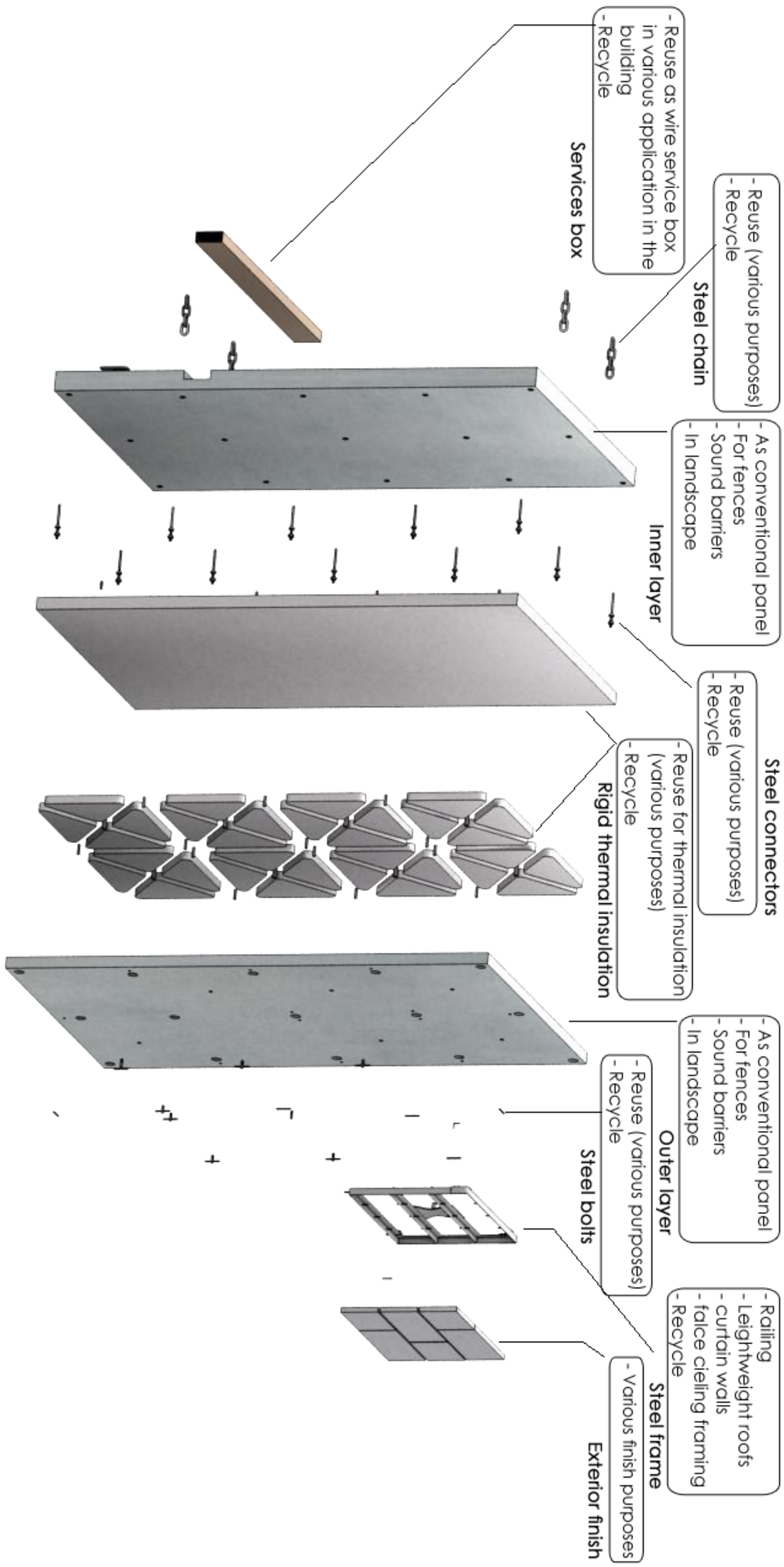


Figure A- 33: Suggested value propositions for the structural and material levels of the sandwich panel system

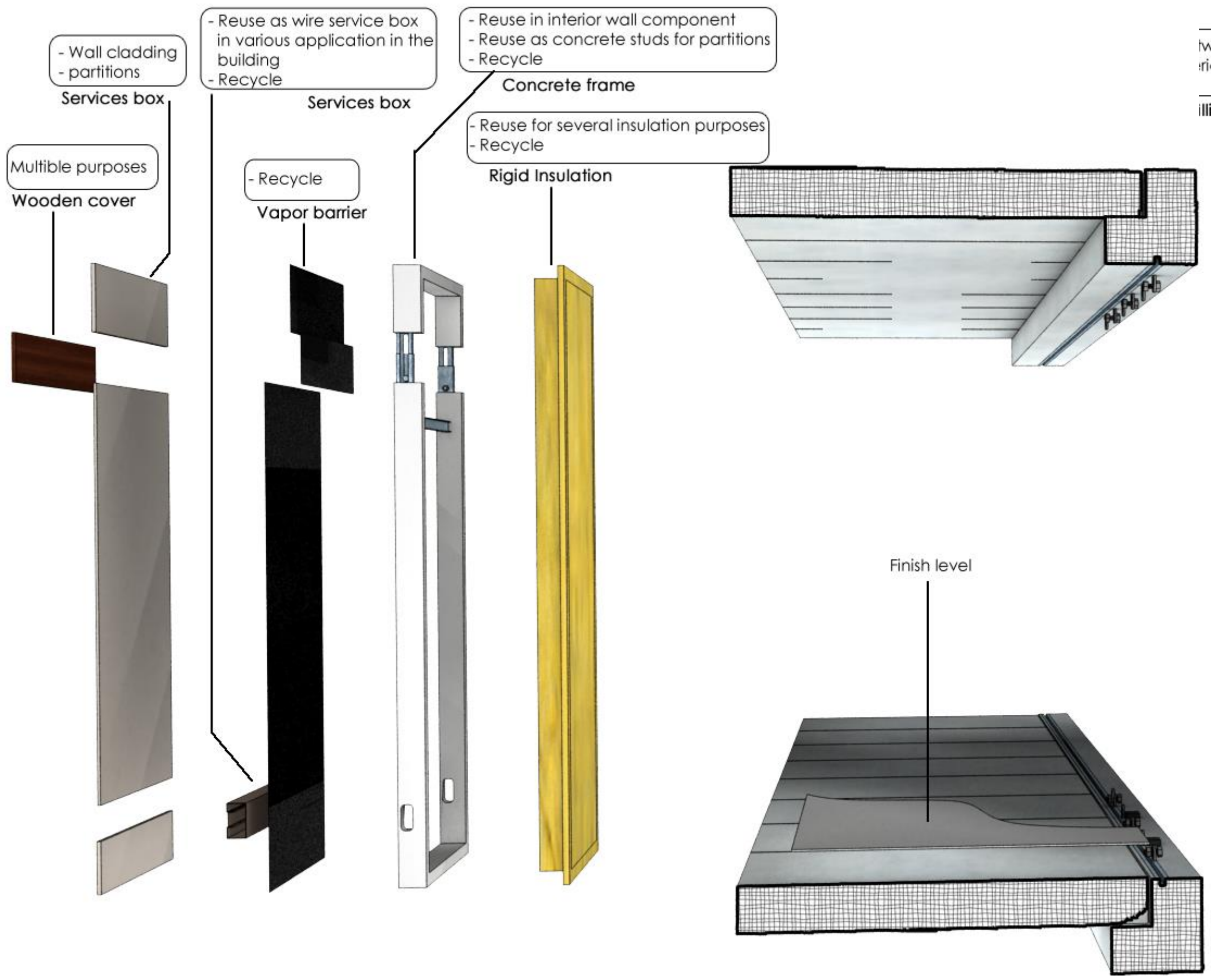


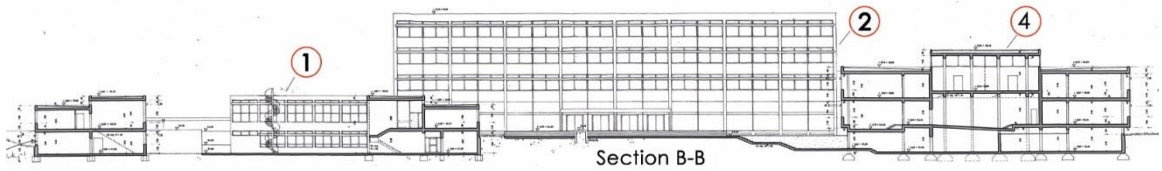
Figure A- 34: Suggested value propositions for the structural and material levels of the fiber reinforced and conventional panel systems

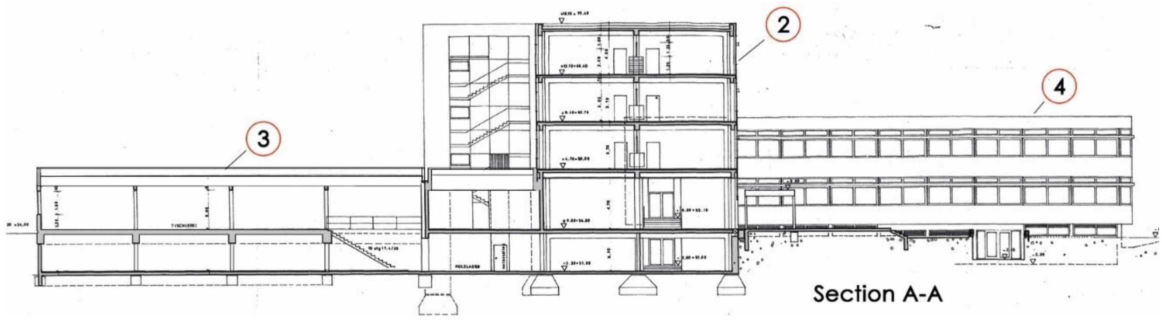
3. Recovery of the conventional panel system parts

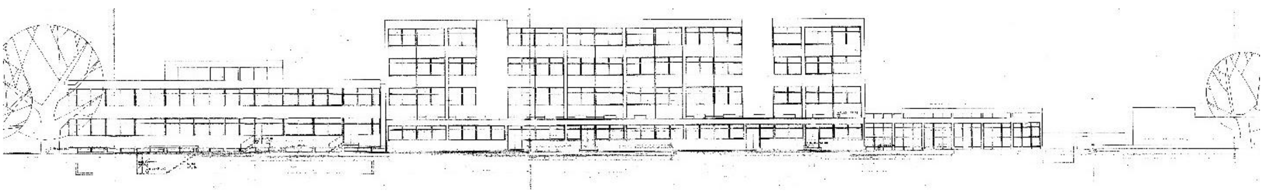
The recovery options for the parts of these systems range from reuse to recycle, however, the reuse potential is determined by the quality of the parts. The priority is for the reuse of the components as a whole and for the same purpose. When there are no reuse options, then the parts could be reused. The systems parts could be reuse for various purposes in the construction of building. Figure A- 33 shows some proposed value proposition for the parts of the system. It is important to mention that some cutting processes may be needed. The value propositions for the exterior part of the conventional precast panel is very similer to the interior part of the precast sandwich panel system. Including the use for fences, in the land scape and in sound barriers for highwayes around resedetial comunities the value propositions are widly available.

Appendix 19: The current design of the case study building

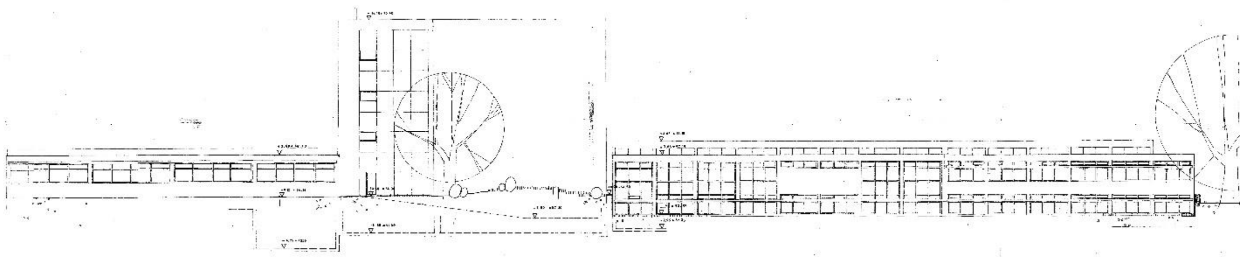
Architectural drawings showing the design of the building of faculty of architecture and land scape, Leibniz University Hannover



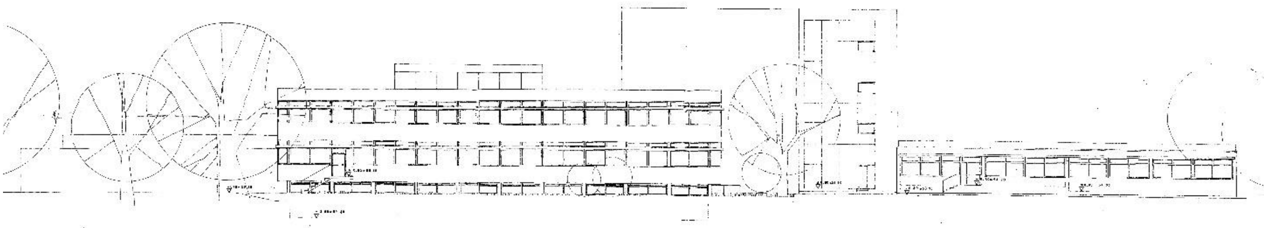




North elevation



West elevation



East elevation

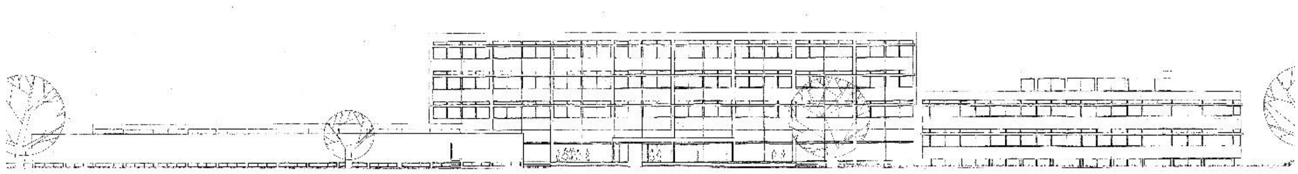
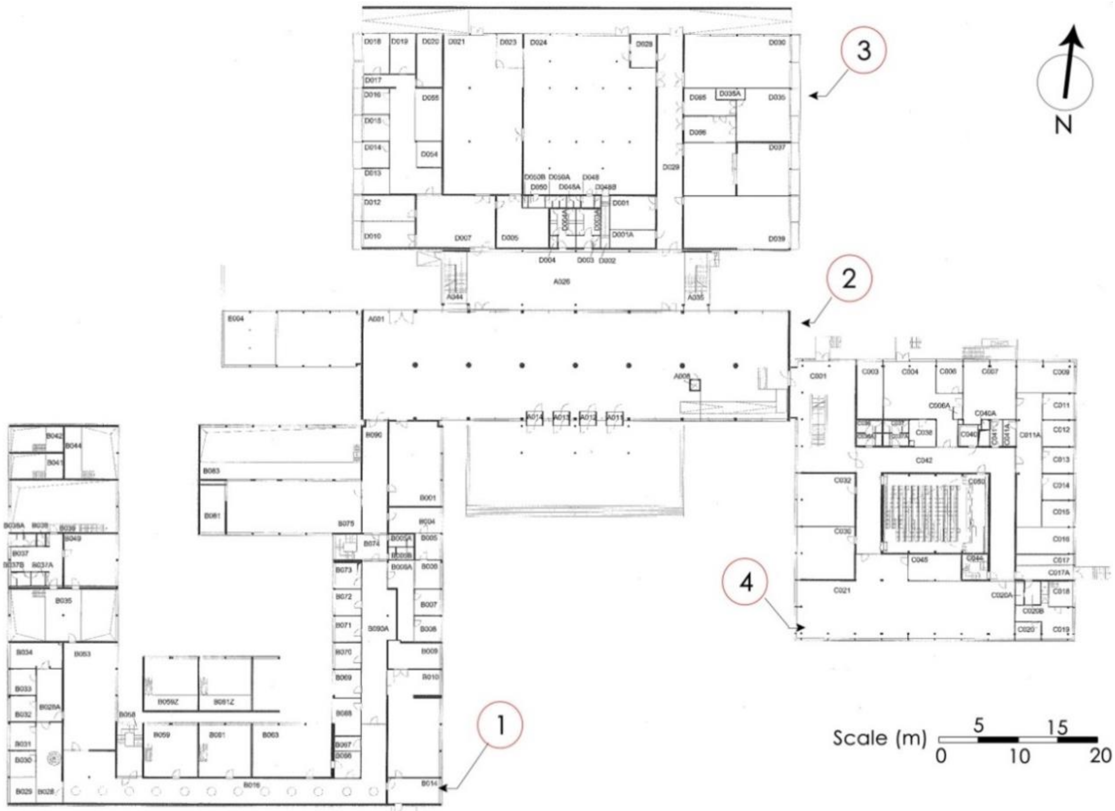
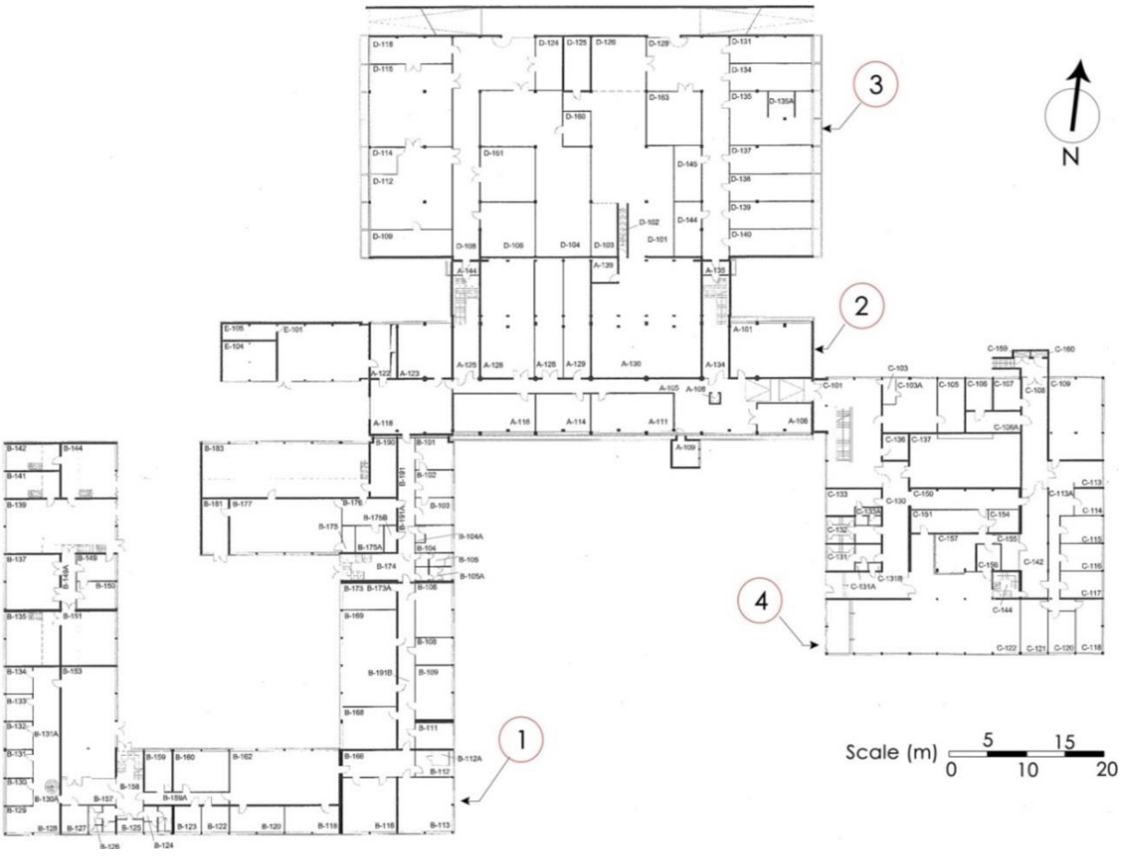


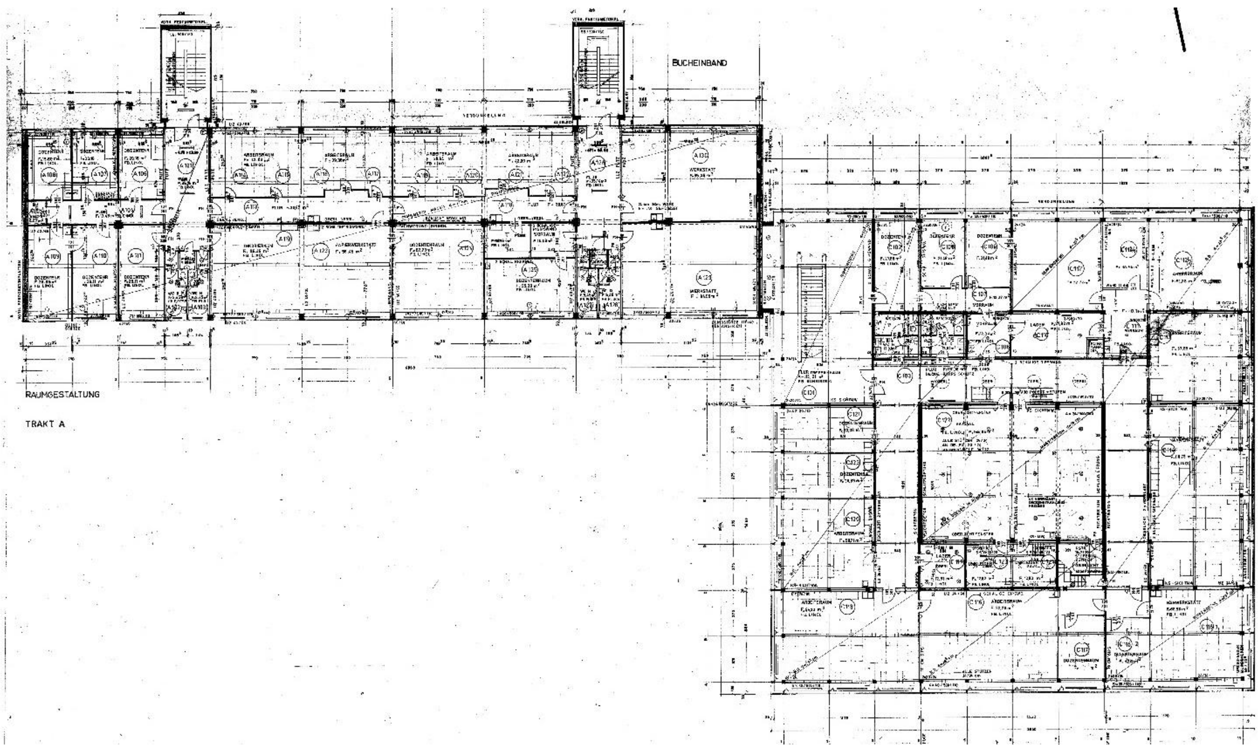
Figure A- 35: Sections and elevations of the case study building



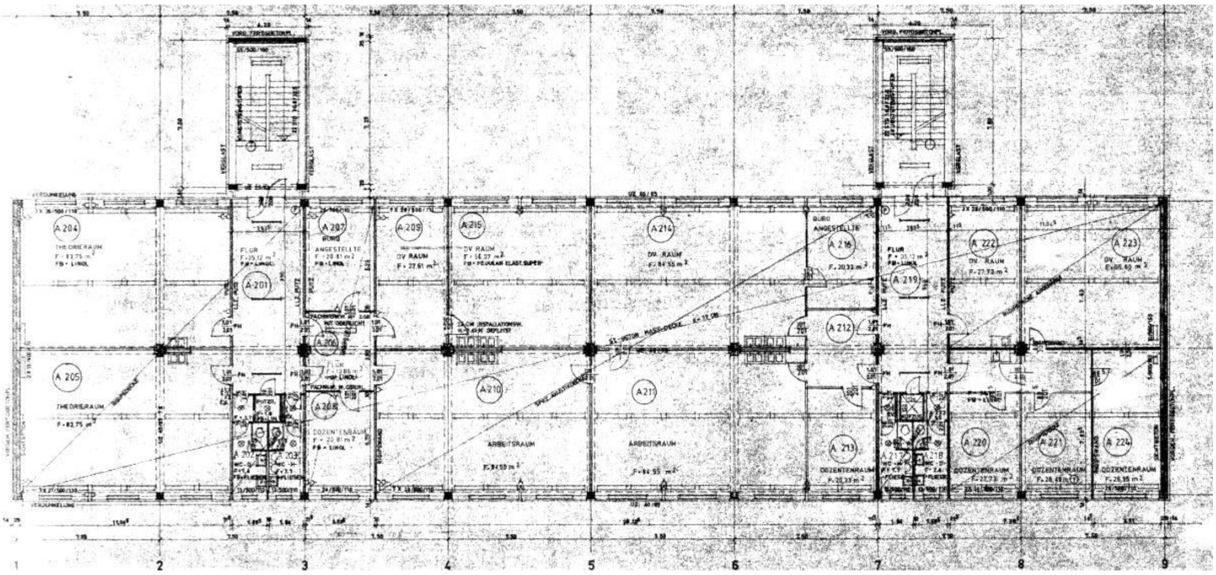
Ground floor plan



Basement plan



First floor plan (Including building 2 and 4)



Typical repeated floor for building 2

Figure A- 36: Floor plans of the case study building

Appendix 20: Construction details of the proposed demountable facades

1. The assembly and construction of the proposed facades of building number one

Two types of precast demountable panels could be used as a part of demountable façade systems for building number one. The first is the vertical panels which can be fixed to the upper and lower beams. And the second is horizontal panels that can be fixed to the lower beam that transfer the its load and a demountable secondary beam. The secondary beam laterally supports the exterior panel and the interior component. These panels are developed based on conventional panels as previously discussed in the previous chapter. This façade system has been chosen due to its suitability to this building in terms of providing a better performance and appearance. The external finishing component could be used to provide the building with an exchangeable façade finish that could be change and reused as required. In the previous chapter this finishing component has been used with sandwich panel systems, however it could be also used with the developed conventional panel system. The following figures show the use of this demountable system its assembly and its construction.

Figure A- 37 shows a schematic plan for the ground floor plan of the building number one and indicates a number of details that clarify the construction of the new proposed demountable facades. It is important to mention that standardization of elements and components has been utilized as much as possible. Standardization facilitates the assembly processes and increases the reuse potential of the elements and components of the facades.

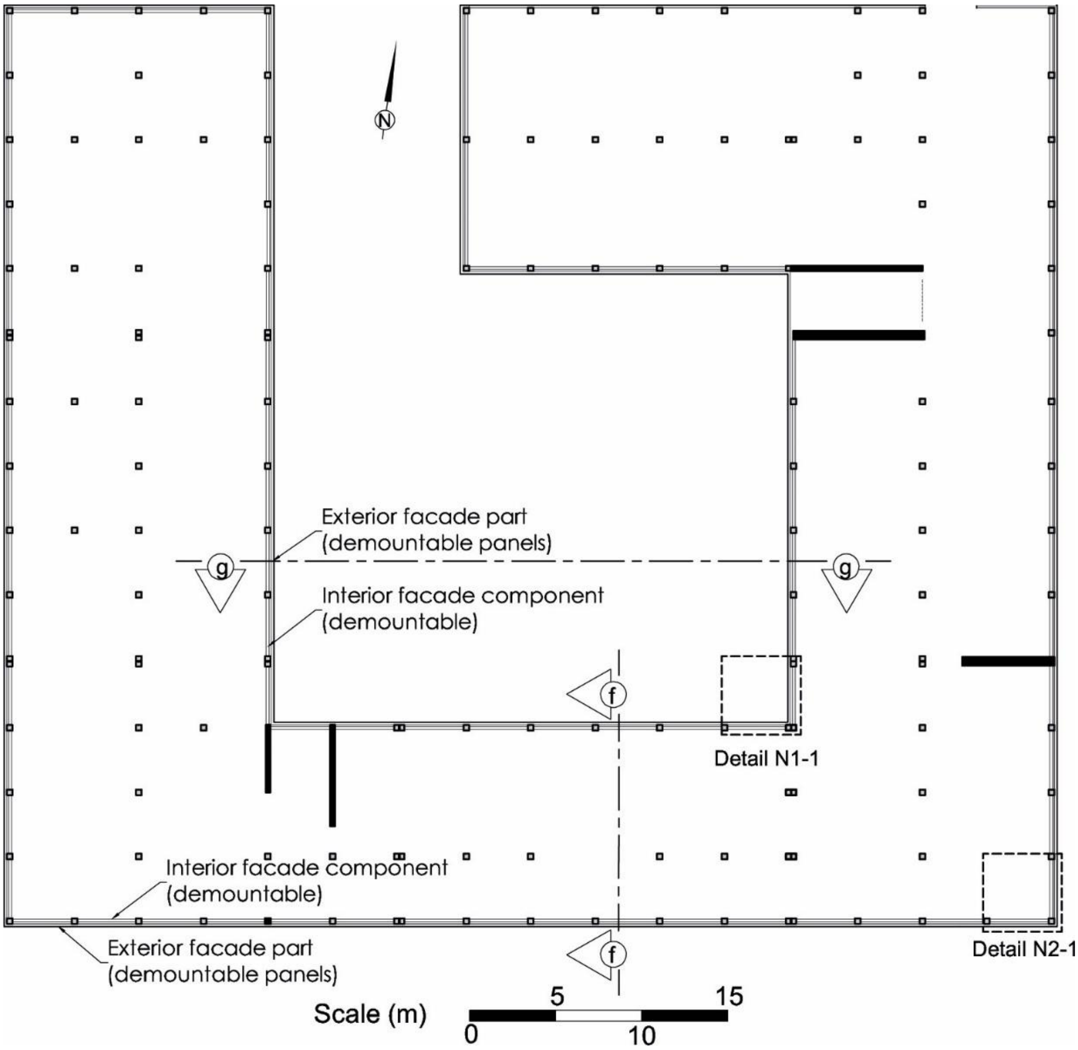


Figure A- 37: Ground floor plan showing the new demountable façades proposal and indicating the construction details (The section made under the windows level to show the construction of the panels taking into the consideration that the original facades design is considered.

Detail N1-1 shows the use of the demountable façade system and the construction and assembly of the exterior and interior components. Due to the use of wide windows, horizontal faced panels and horizontal interior component will be use. A horizontal demountable beam will be used as an intermediary between the exterior and interior components and to fix them to the adjacent columns.

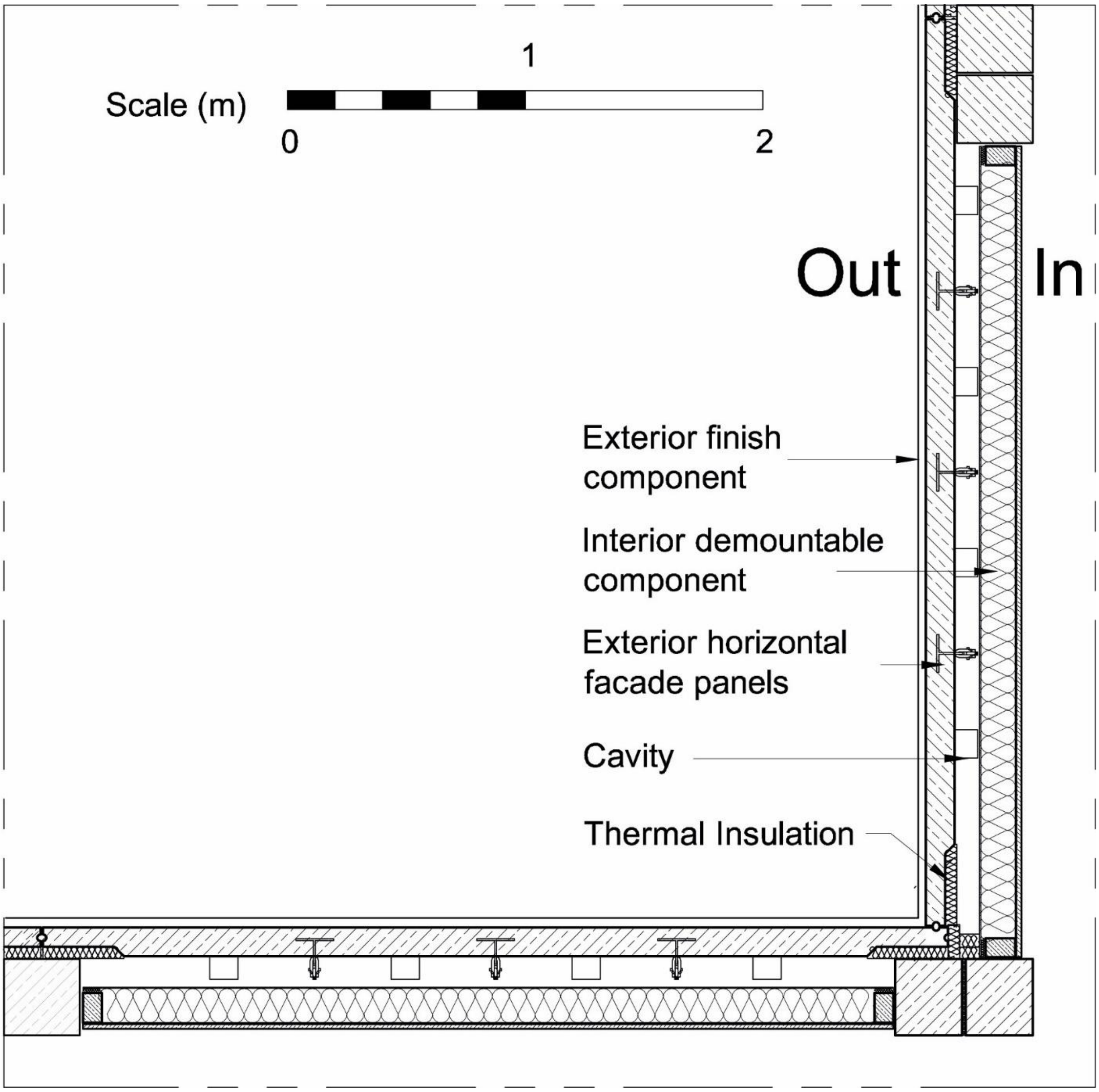


Figure A- 38: Detail N1-1 showing a typical horizontal section

Figure A- 38 shows the assembly of the façade components at the inner corner of the court yard. Typical horizontal conventional panels were used, however, special panel's length at the corners only might be required. Typical horizontal demountable interior components are also used. The interior components are fixed using pins from below and lateral tie back connections provided by the secondary fixing beam. The secondary fixing beam works as a base element for the various façade components including the window, the interior component and the exterior panel.

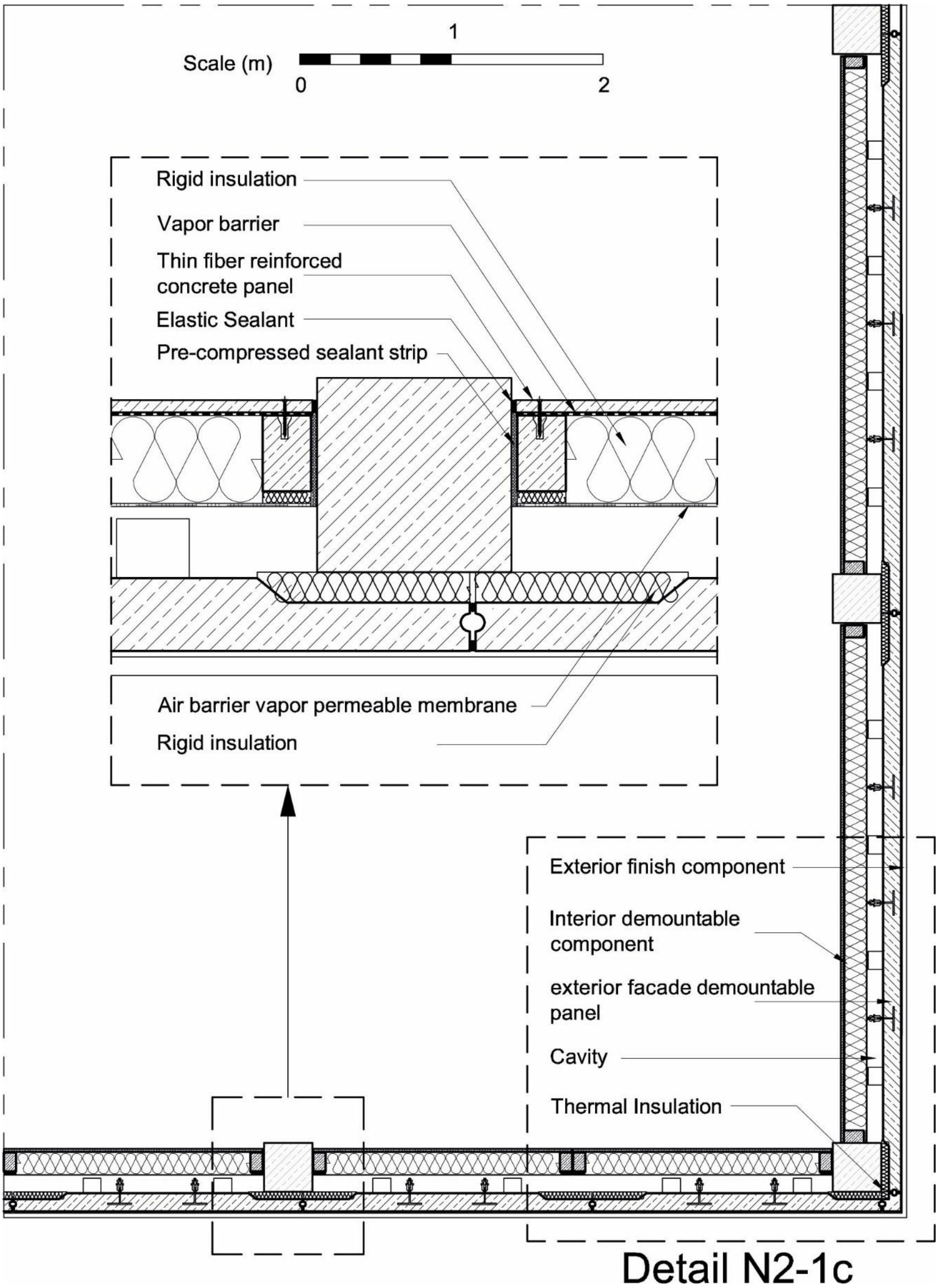


Figure A- 39: Detail N2-1b showing a horizontal section at the ground floor below the windows level

Figure A- 39 shows the construction of the façade where two vertical panels and interior components have been used in the solid façade. Horizontal panels and interior components have been used for facades that have wide windows.

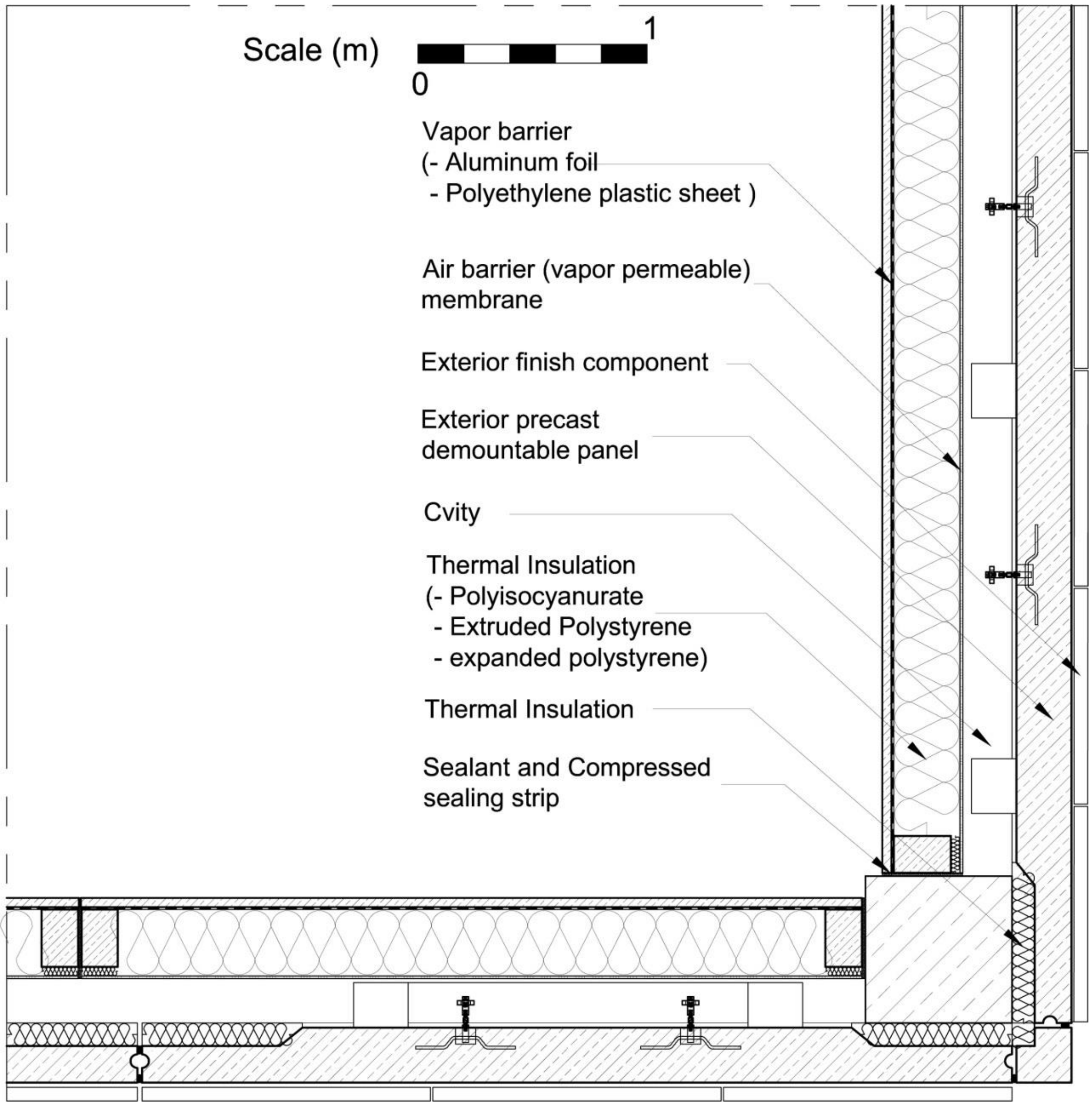


Figure A- 40: Detail N2-1c

Figure A- 40 shows how the use of insulation material at the panels ends help in preventing from shaping thermal brides especially at column and beams areas.

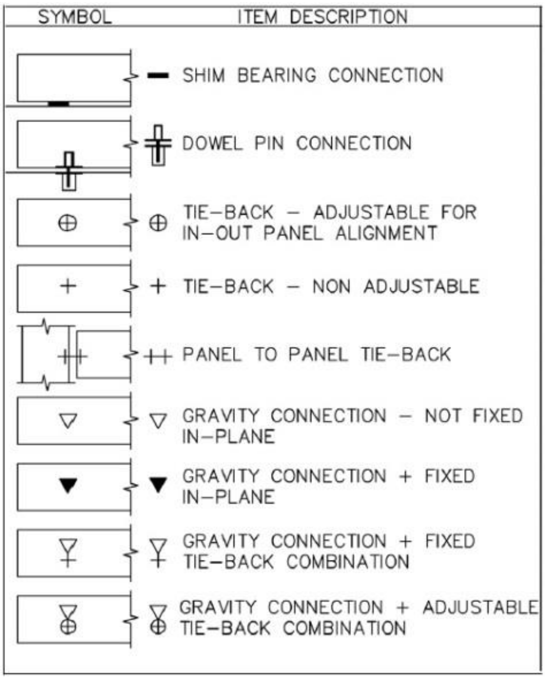


Figure A- 41: Connections legend ((NPCA), 2014)

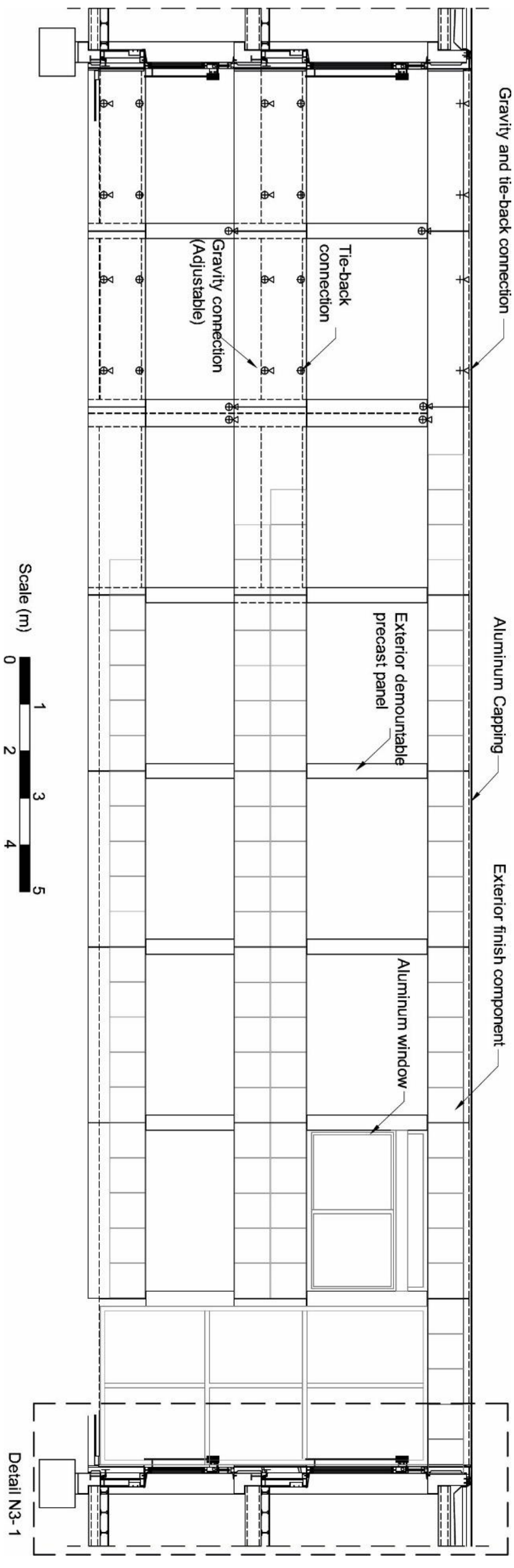


Figure A- 42: Section g-g showing the use of demountable facades and the exterior finish components and their construction

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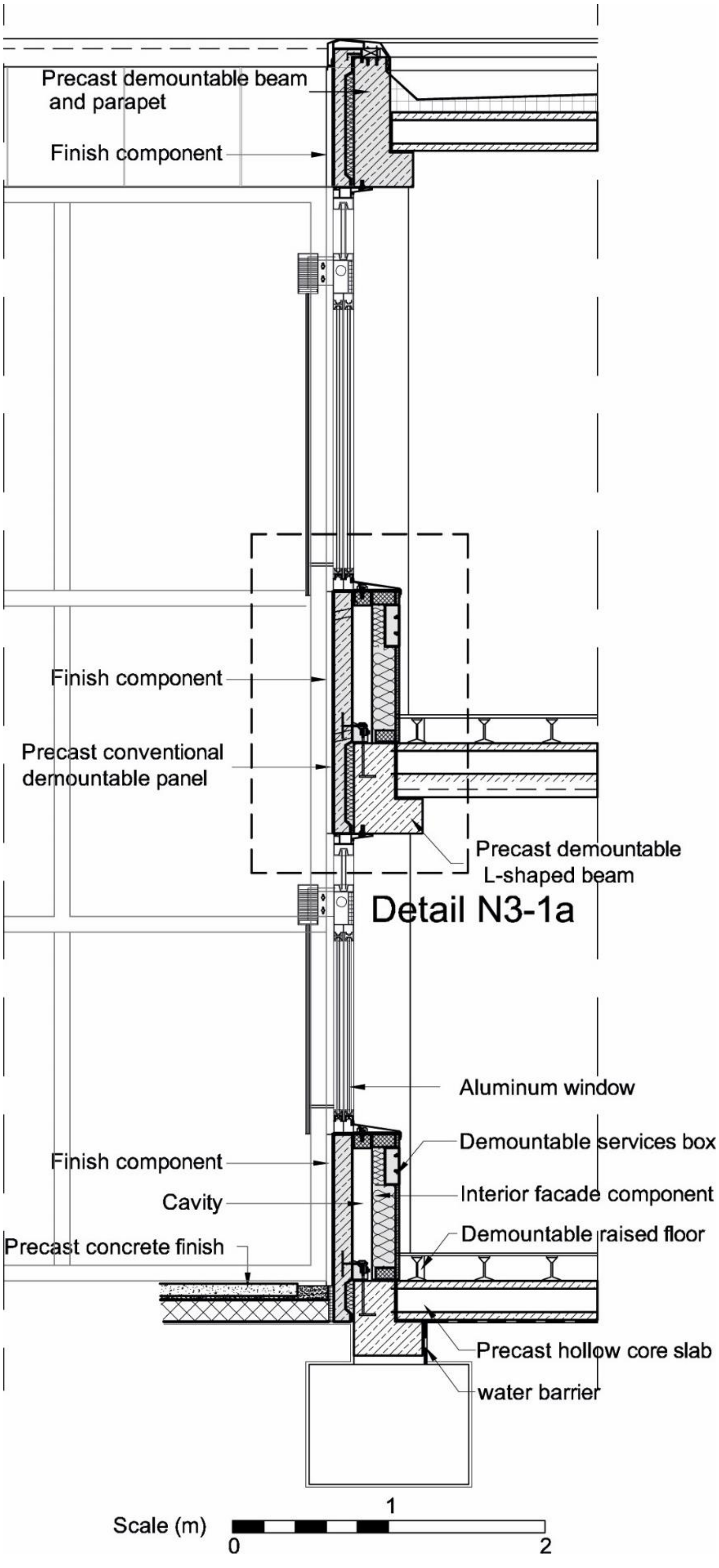

Figure A- 43: Section N3-1 showing the construction of demountable façade system

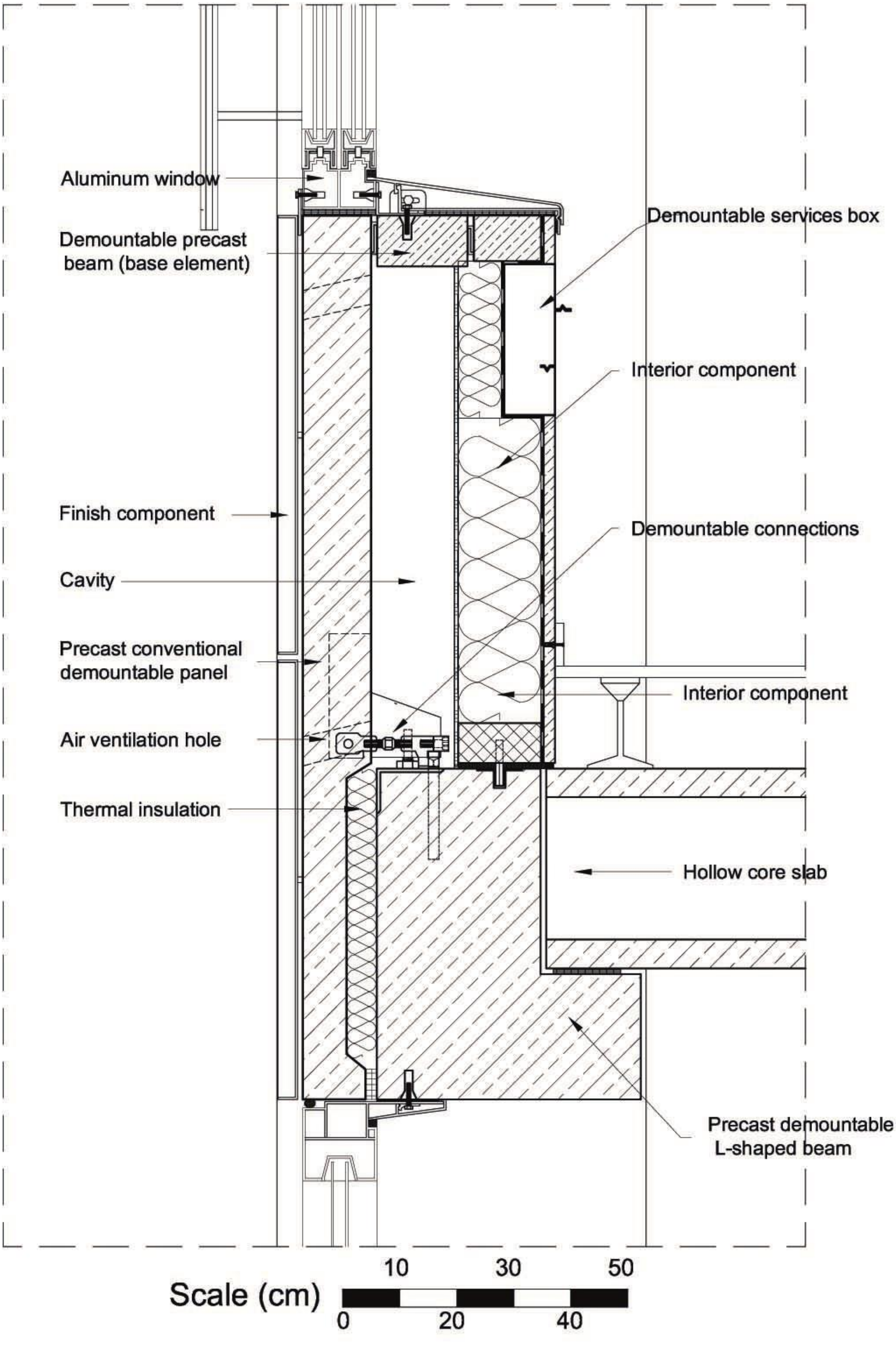

Figure A- 44: Detail N3-1a showing the demountable façade parts and construction

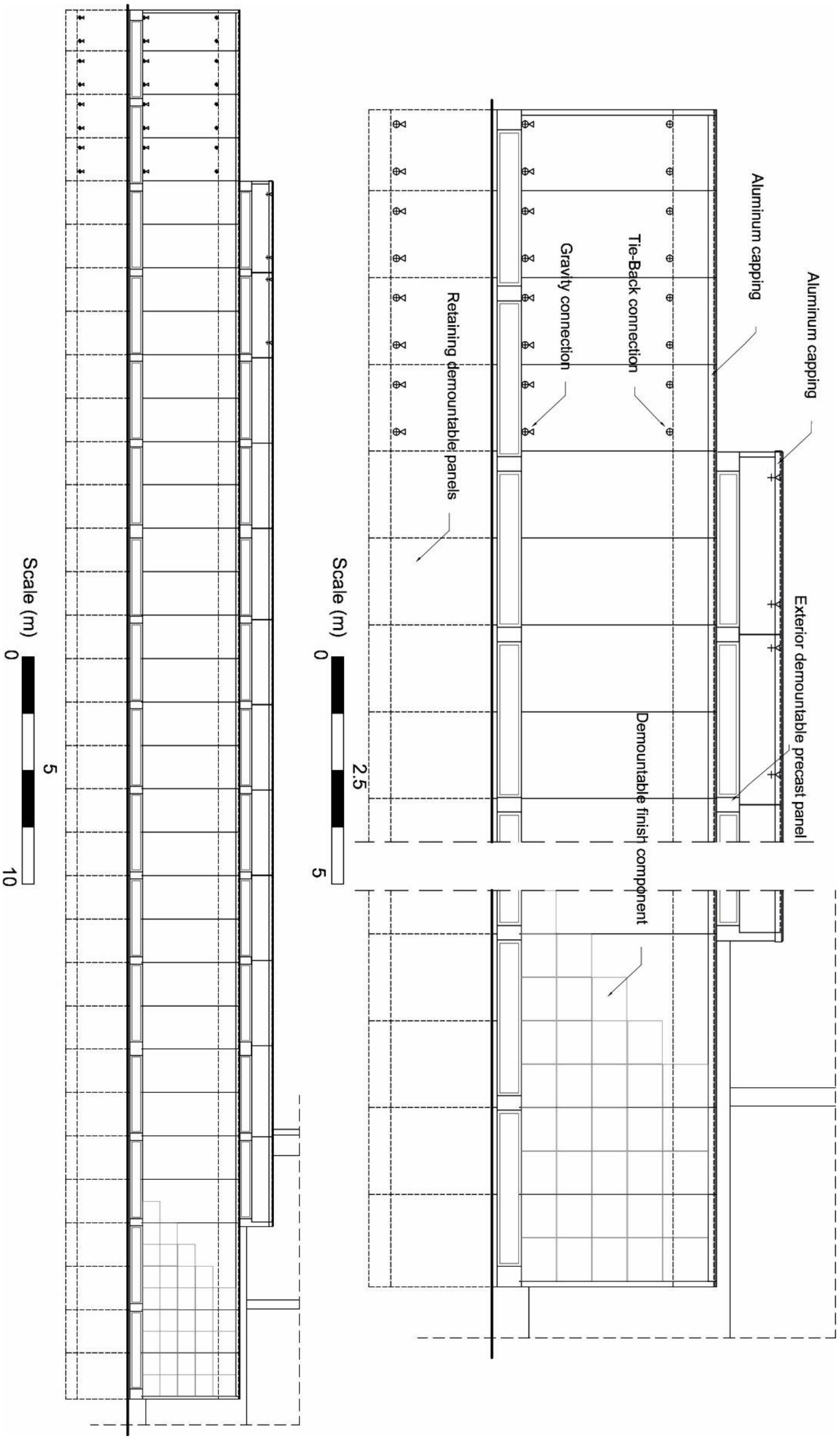

Figure A- 45: South elevation of building number one

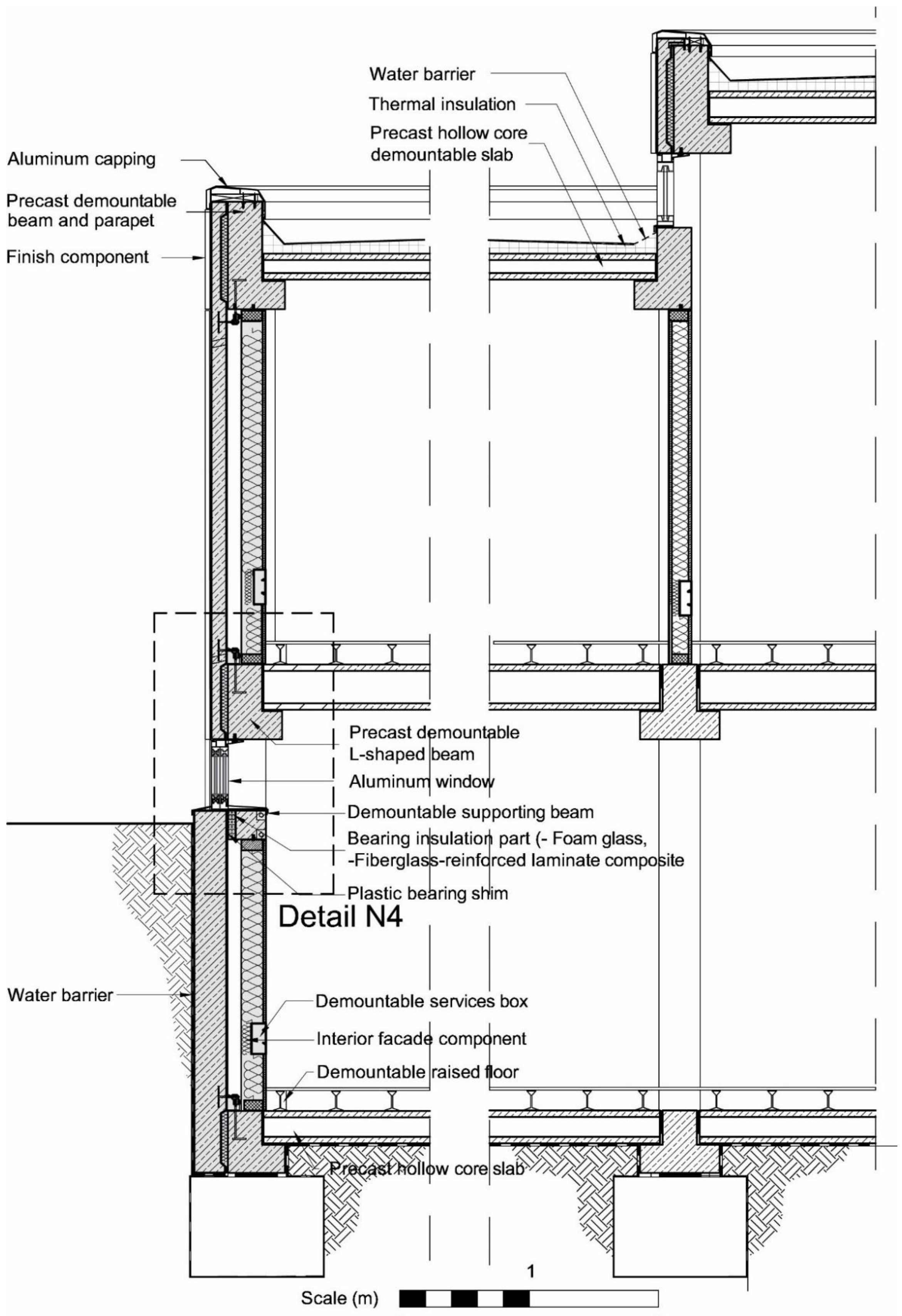

Figure A- 46: Section f-f showing the construction of the south elevation of building number one

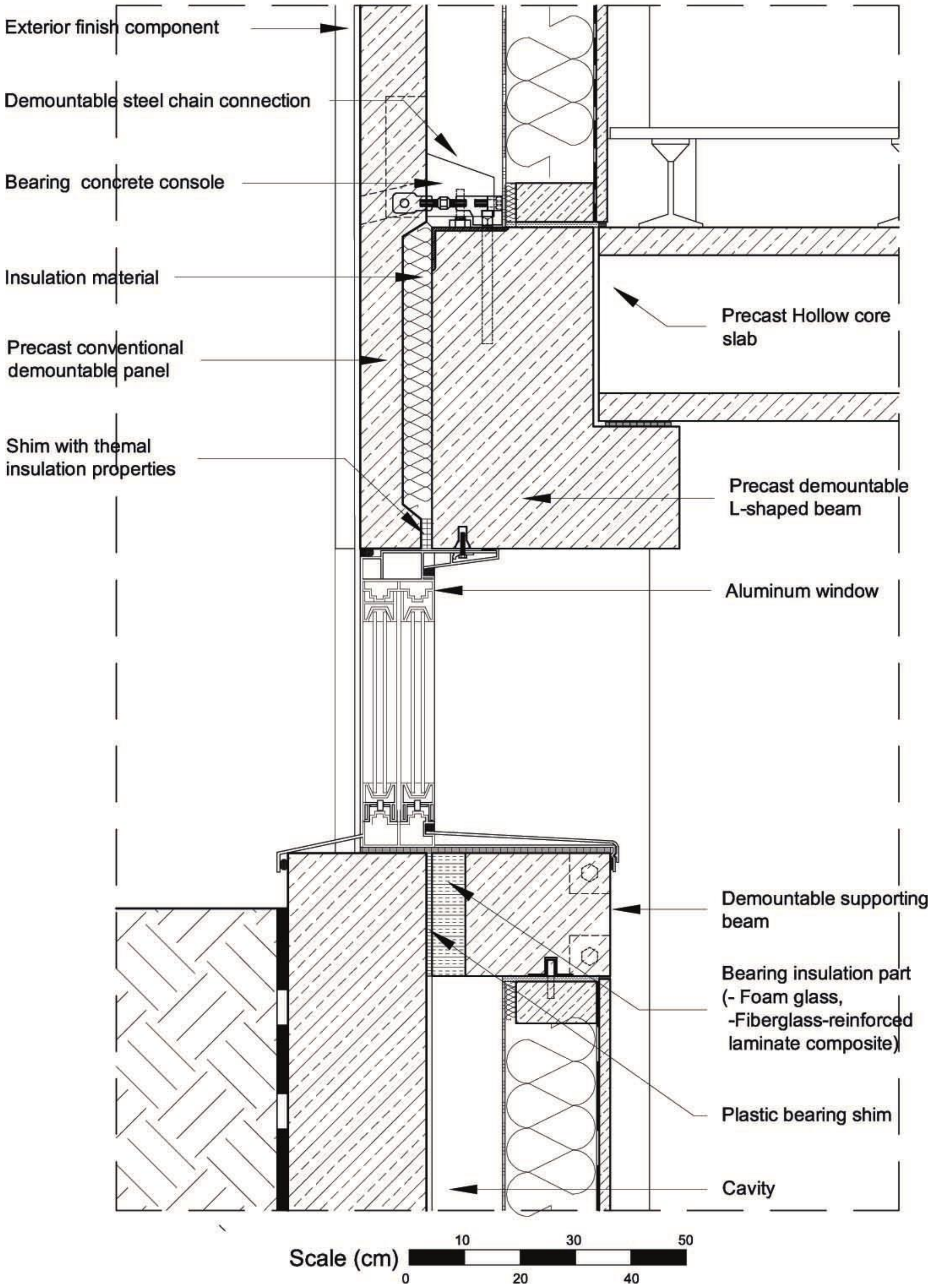

Figure A- 47: Detail N4 showing the construction of the lower part of the south façade of building number one

2. The assembly and construction of building number two

The following drawings and details show the construction of the new proposed demountable facades for building number two. As in building number one vertical panels and interior components have been used for the west and east solid wall facades. Alsoo horizontal panels and interior components have been used for the north and south facades. Figure A- 48 shows a schematic plan for the new facades proposal for building number two and specifies some details.

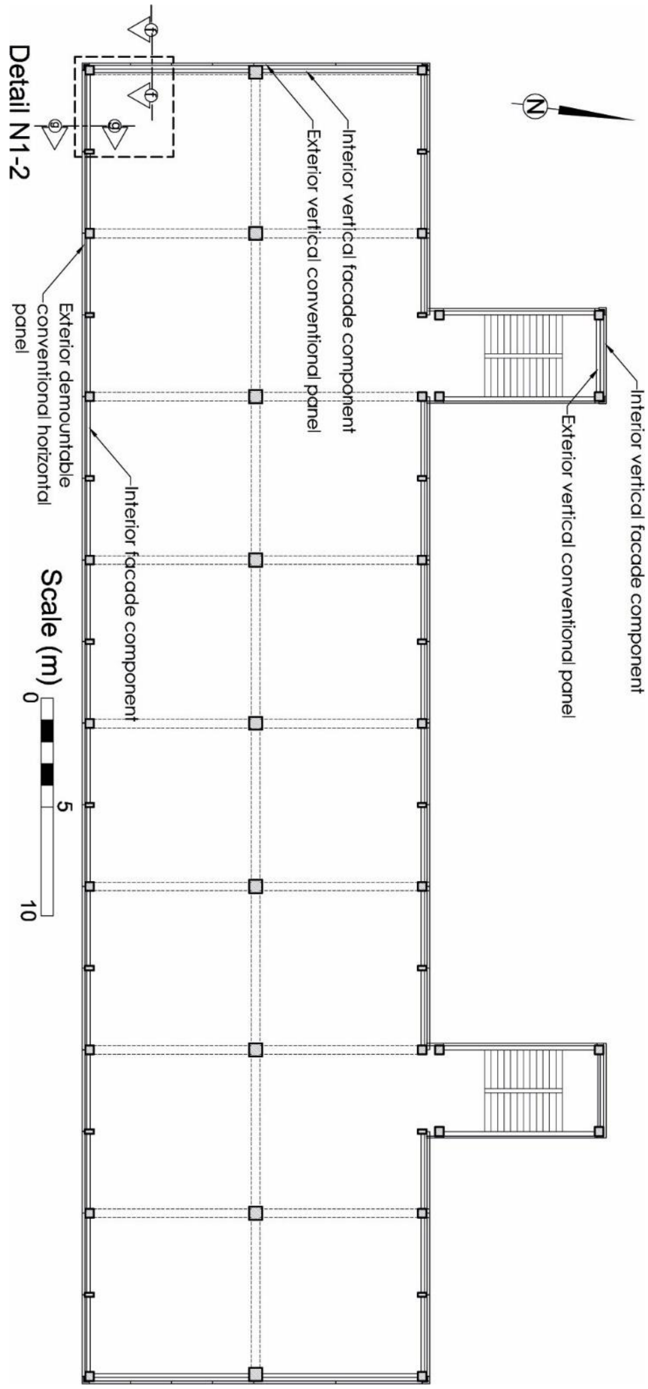

Figure A- 48: Building number two typical plan (1st – 3ed floors) showing the façade construction

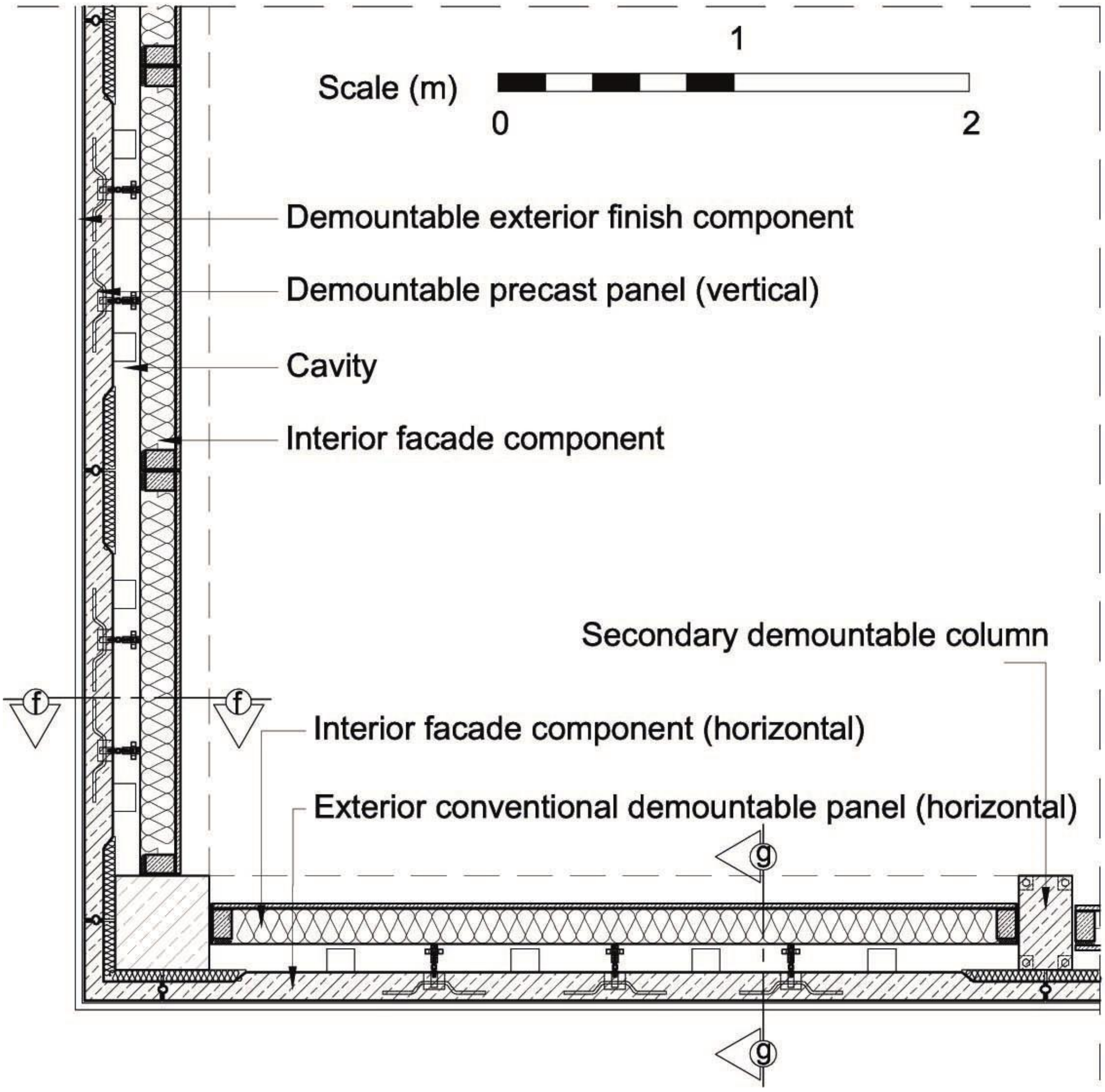

Figure A- 49: Detail N1-2 Showing the arrangement of the façades component and elements (The section has been taken under the windows level).

Figure A- 49 shows the construction of the facades where vertical panels and interior components have been used for the solid wall facades. Horizontal panels and interior components have been used for the north and south facades which have wide windows. Also, demountable secondary columns and beams have been used to fix the facades parts.

The following drawings include sections details and elevations that provide a complete picture about the use and construction of the proposed demountable façade systems.

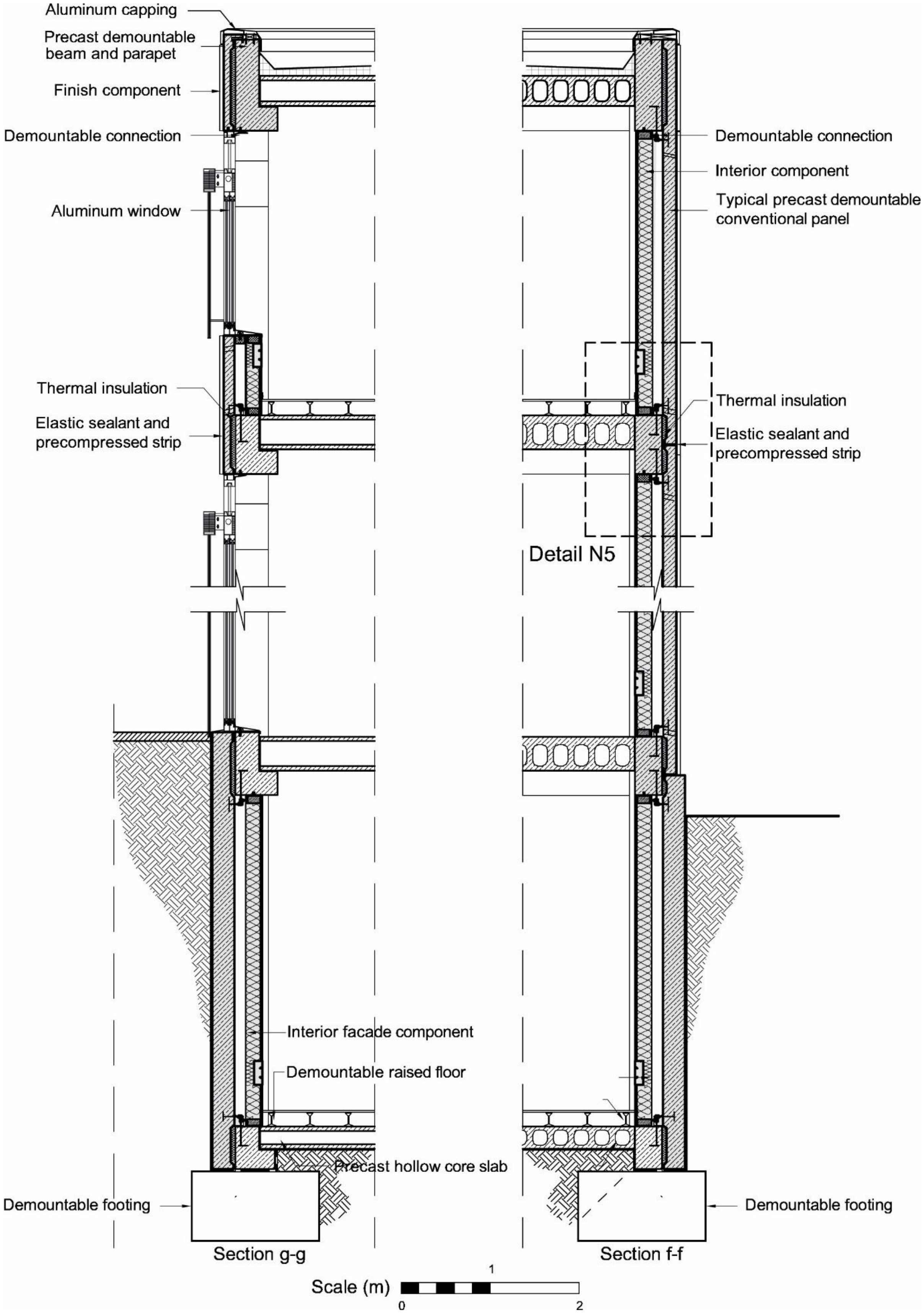

Figure A- 50: Sections f-f and g-g

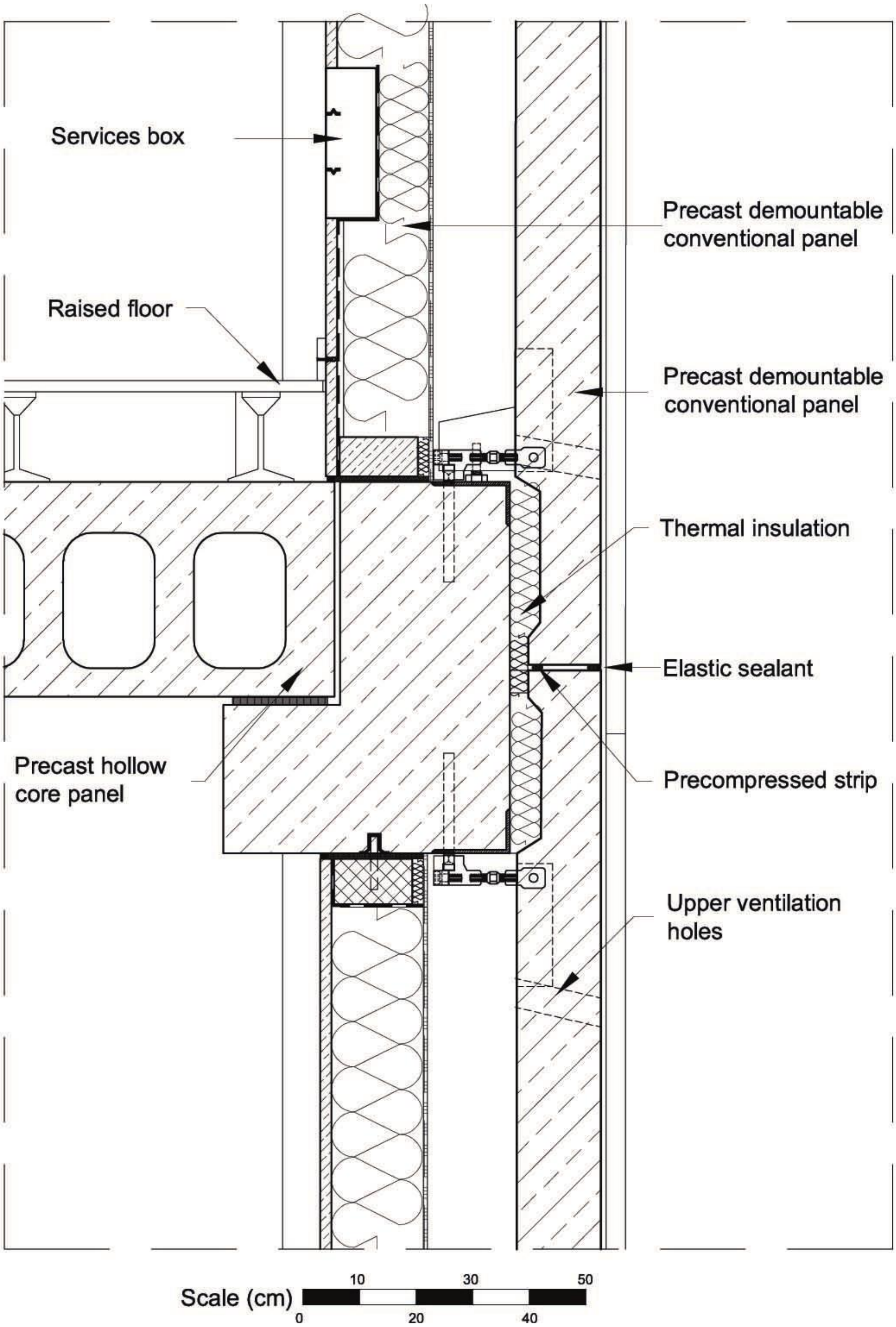

Figure A- 51: Detail N5 showing the construction of the demountable façade system at the joint

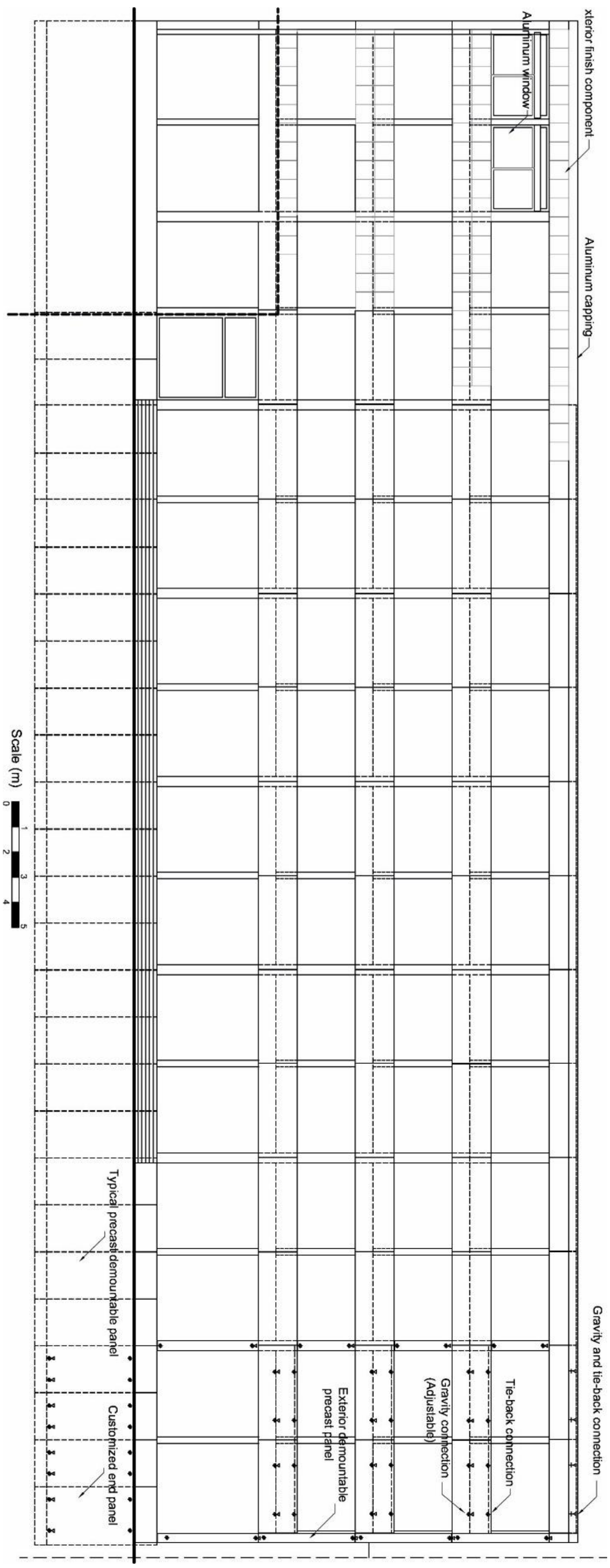

Figure A- 52: Building umber two (front elevation)

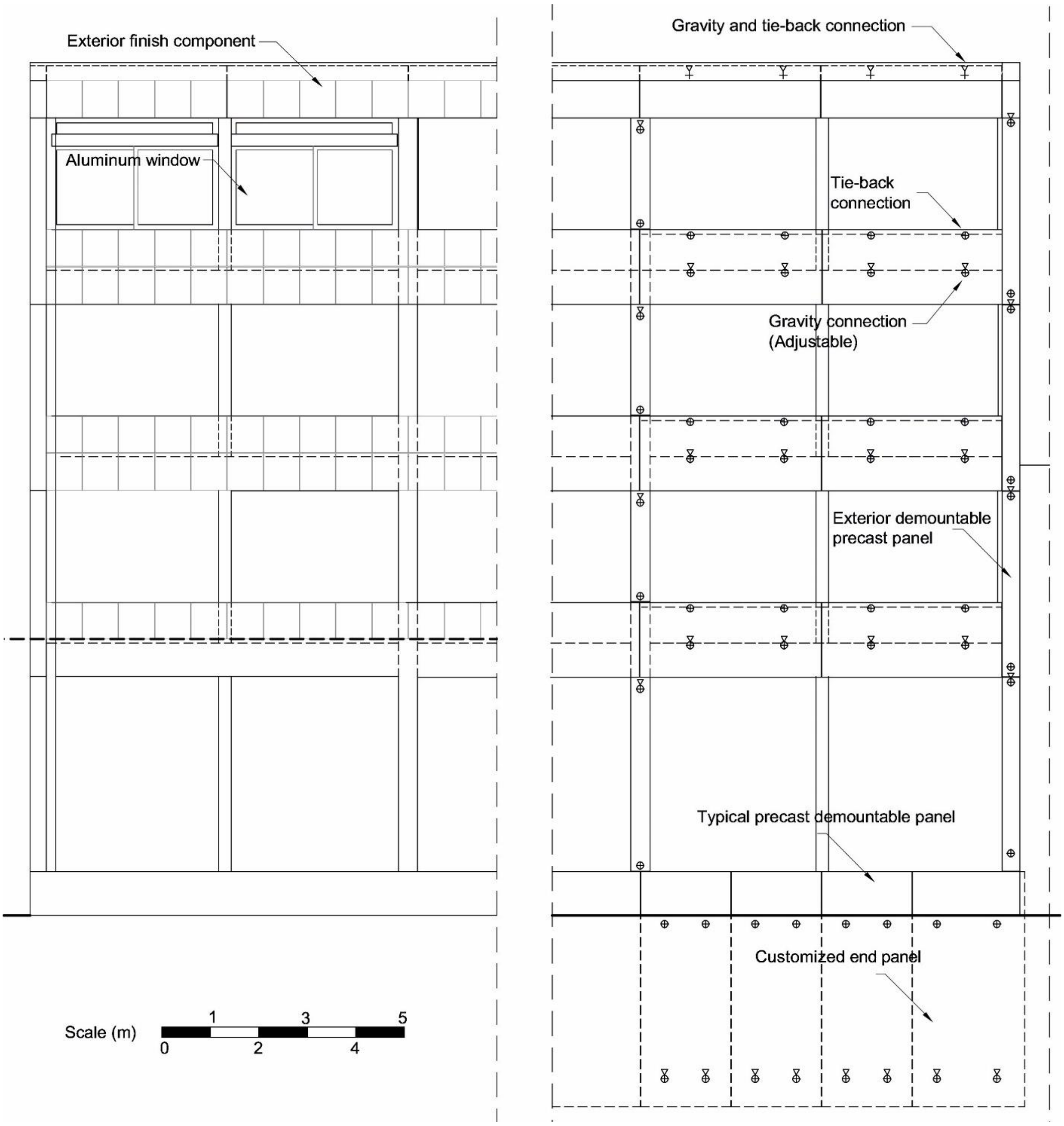

Figure A- 53: Partial details of building number 2 from elevation showing panels and finish component distributions and their connection types and places

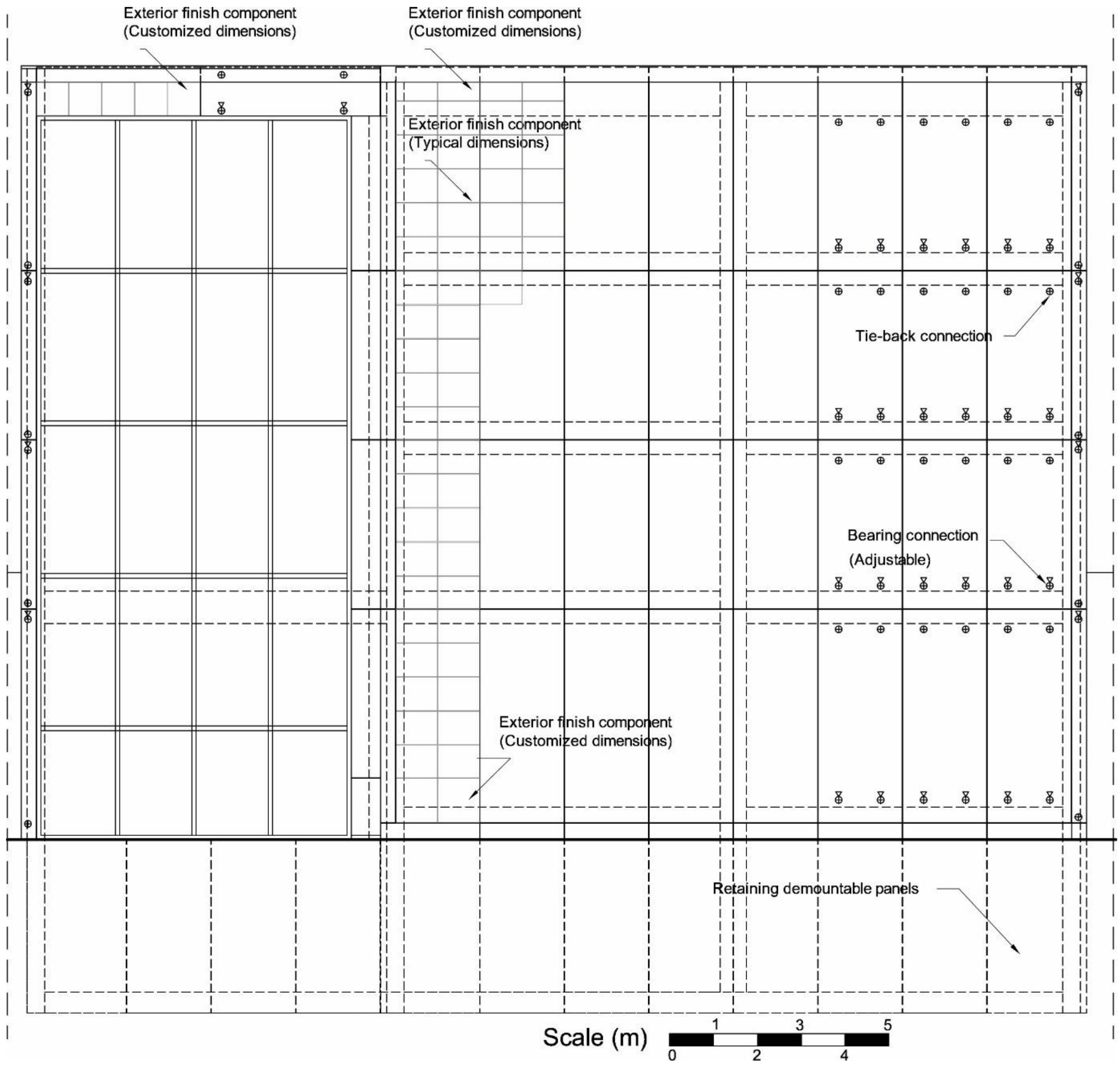

Figure A- 54: West elevation of building number two, panel and connection distribution are shown.

3. The assembly and construction of building number three

To avoid repetition, the same vertical and horizontal faced systems - as in the previous examples in building number one – could be used for building number three. this part of the building has wide windows in most of its facades as in the North, West, East facades and solid walls in some part of the south façade.

4. The assembly and construction of building number four

The following details show the construction of the demountable façade system of building number four. The facades of this building are distinguished from the previous facades of the other buildings by the use of cantilever where the facades are fixed. A demountable secondary beams and columns are used to support the facades. The following details show the construction of these facades.

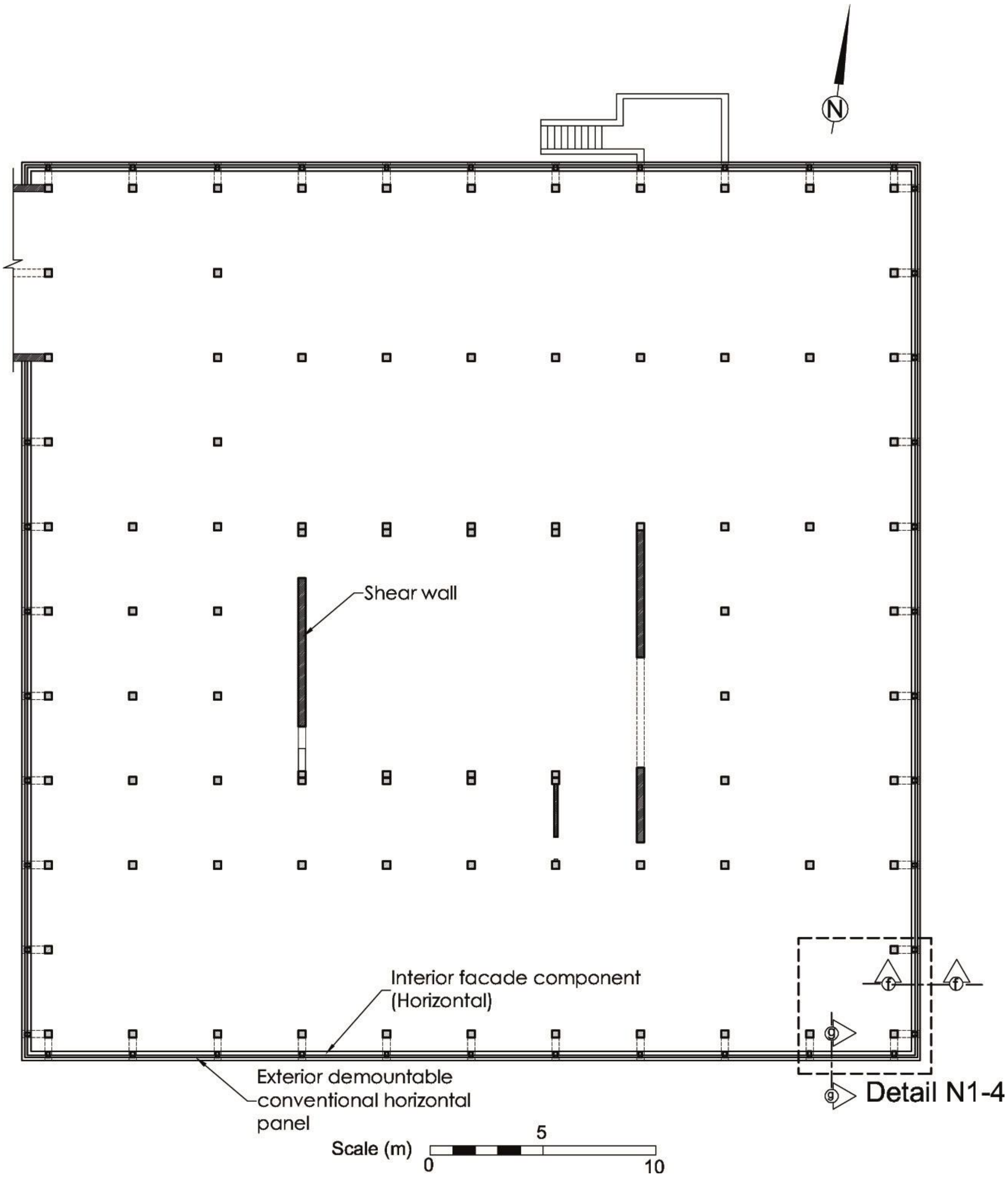

Figure A- 55: A schematic ground floor plan of building number four showing the construction of the facades

Figure A- 55 shows a schematic plan that illustrates the facades of the typical ground and first floors of building number four and indicates further details and sections.

Figure A- 56 shows a horizontal section under the windows level of the cantilever facades and clarifies the construction of its parts and components. For fixing of the facades components and parts secondary demountable columns and beams have been used.

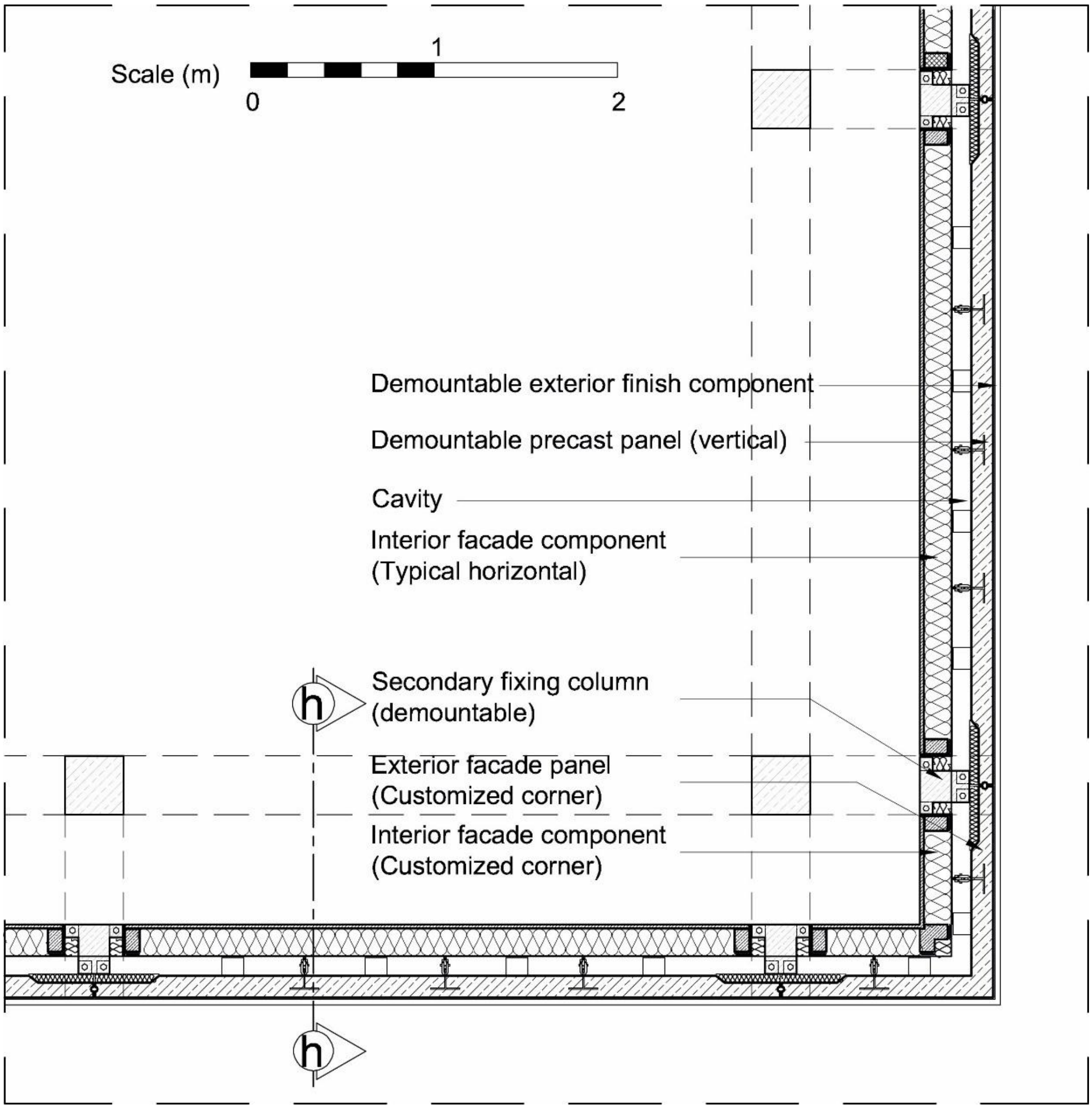

Figure A- 56 : Detail N1-4 showing the distribution of façade components and parts and their construction (the section has been taken under the windows level)

Typical horizontal conventional panels and interior components have been considered for the construction of the facades of this building, however, a customized corner parts were also required.

The following sections and details provide a complete picture of the facades assembly and construction. Figure A-57 shows tow possible solution to the cantilever facades. To the left: (the extended console system) where at every floor level an extended console is used to support the demountable secondary beams and columns that support the demountable facades. To the right: (a hanging system) is used where only a console at the higher ceiling level is utilized to hang the demountable secondary beams and columns that support the demountable faced system.

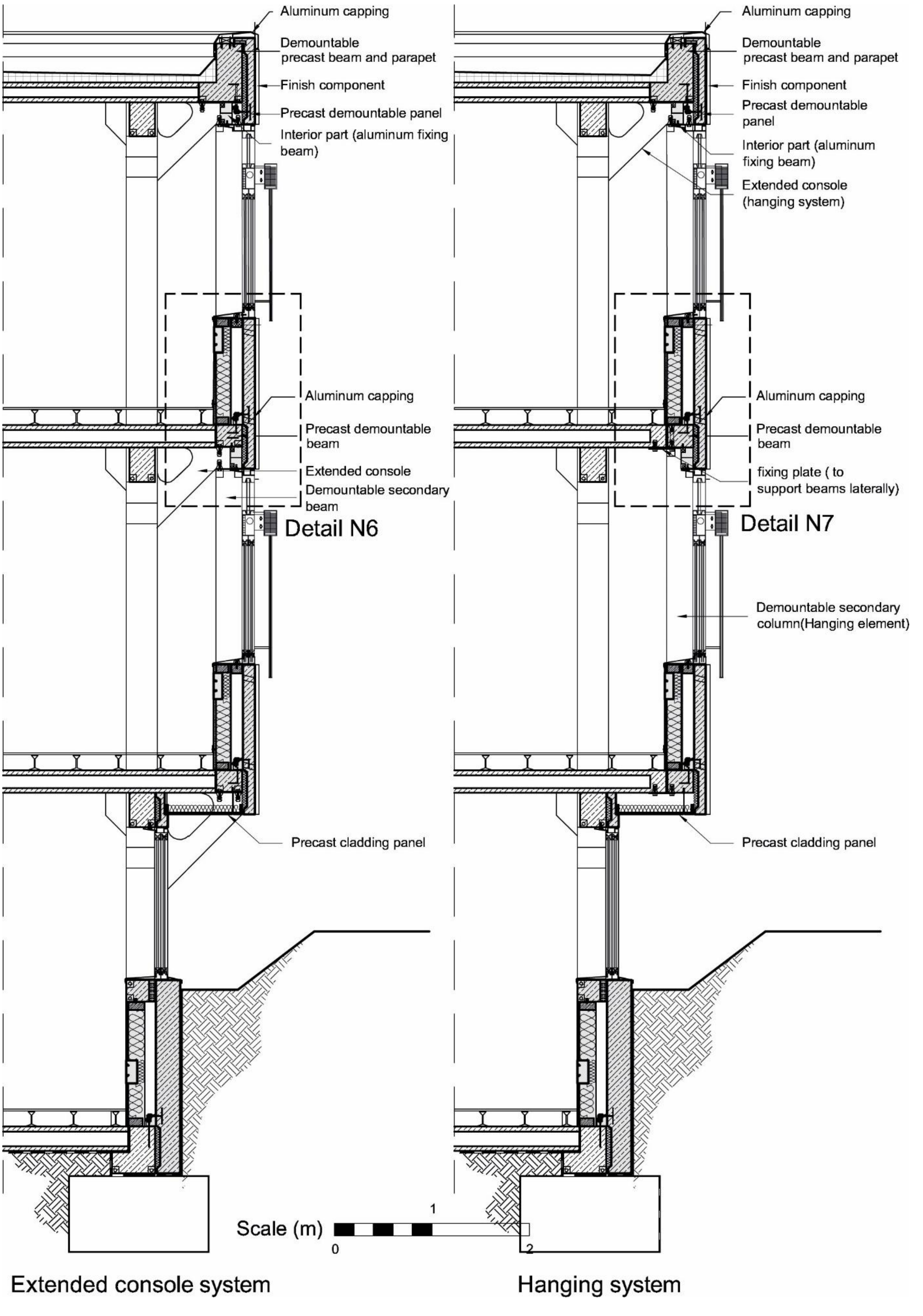

Figure A- 57: Section h-h

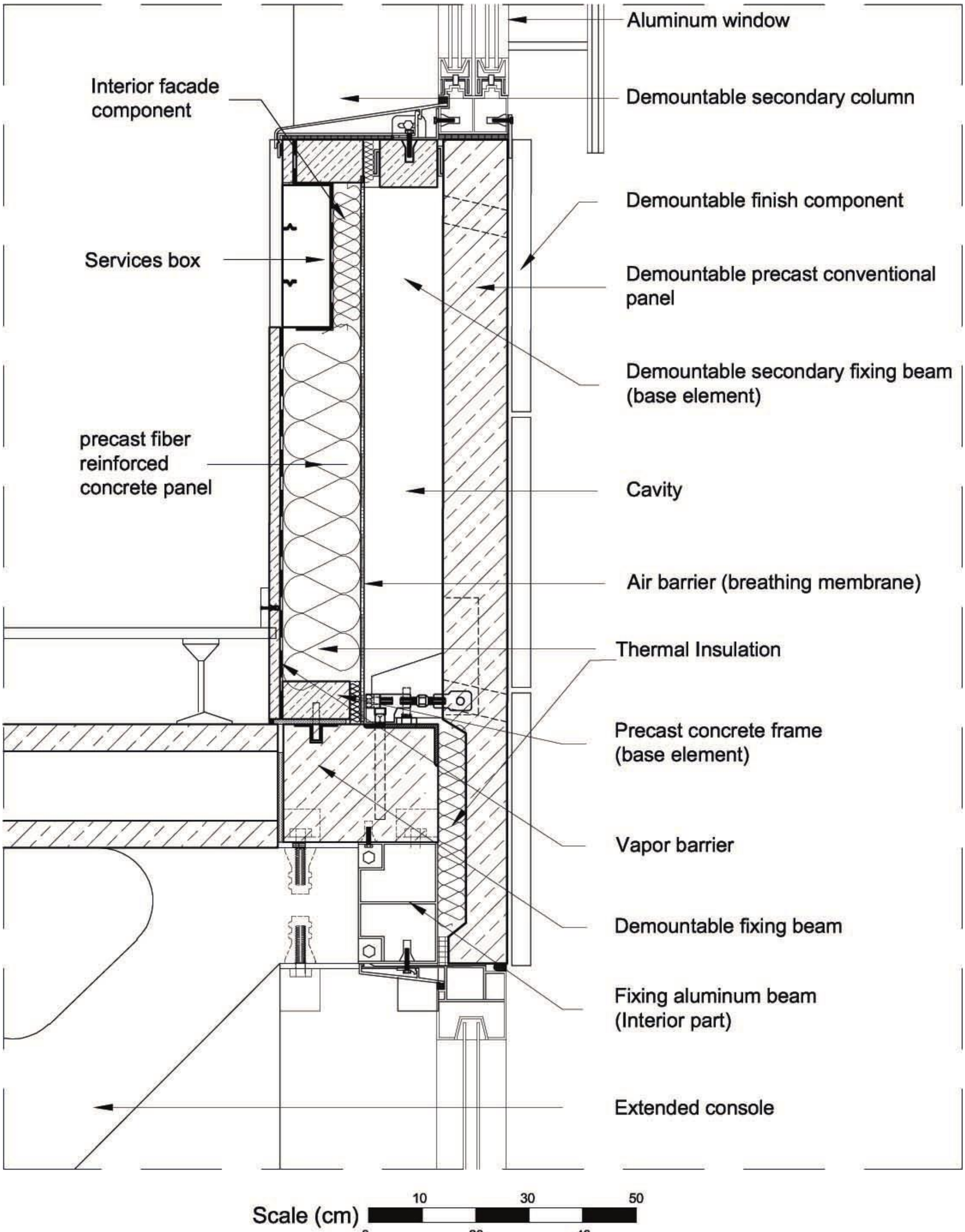

Figure A- 58: Detail N6 showing the construction of building number four façades and their parts and components (Extended console system)

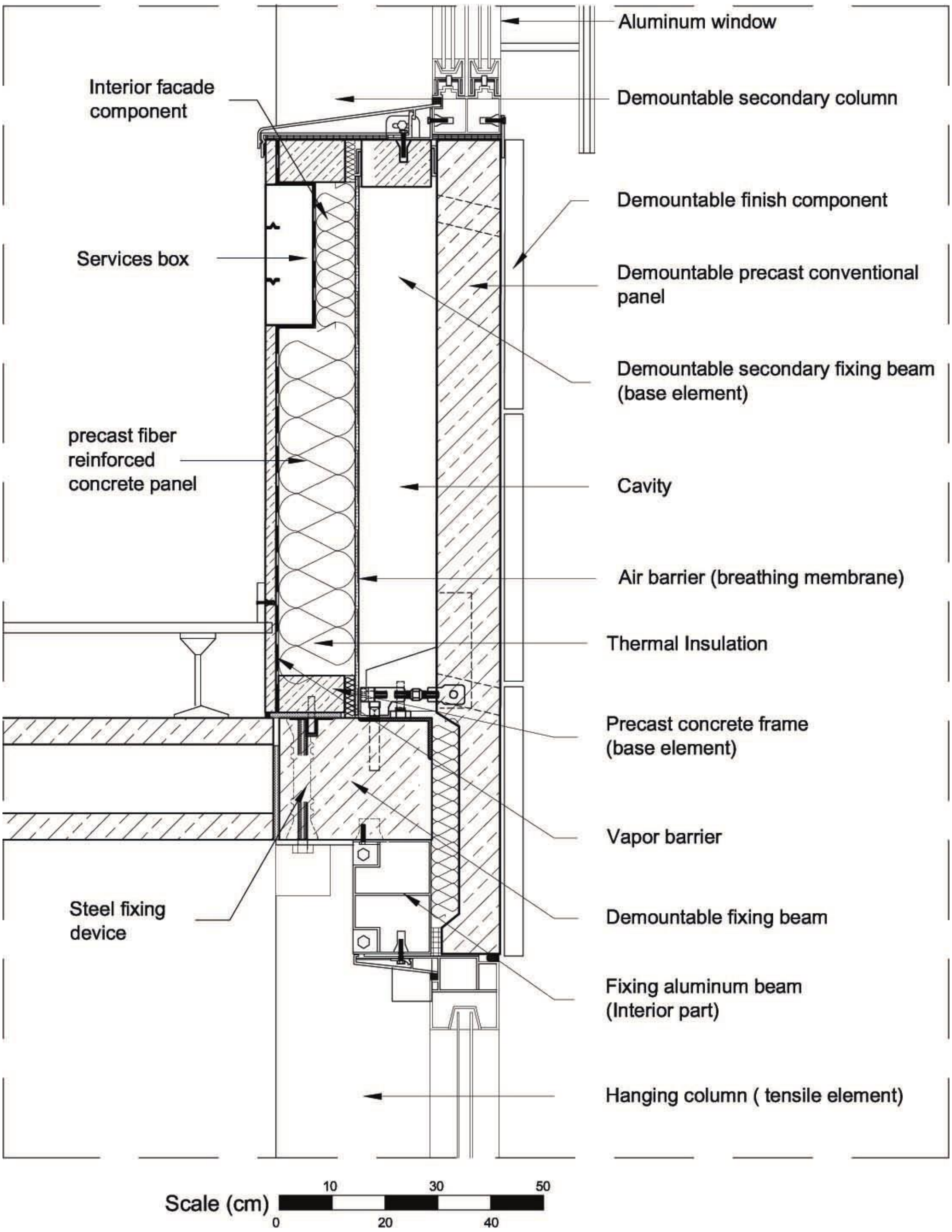

Figure A- 59: Detail N7 showing the construction of building number four façades and their parts and components (Hanging system)

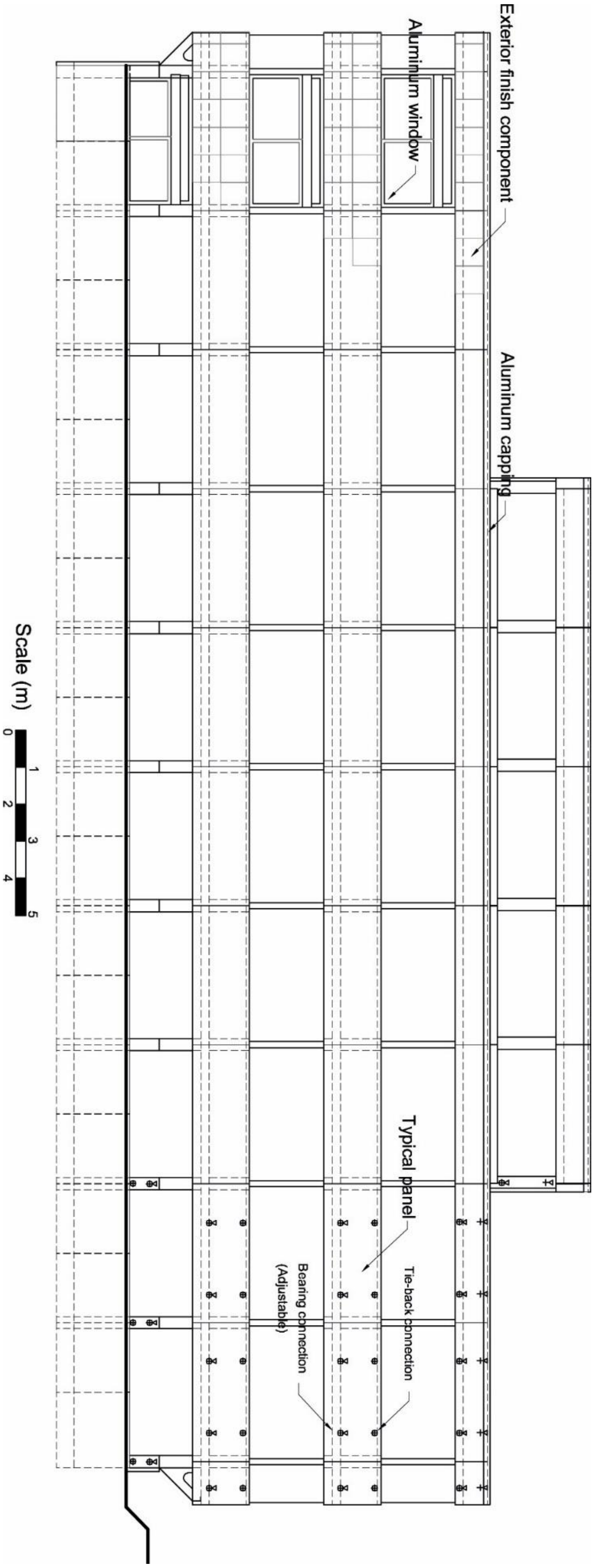

Figure A- 60: South elevation of building number four showing the construction of precast panels