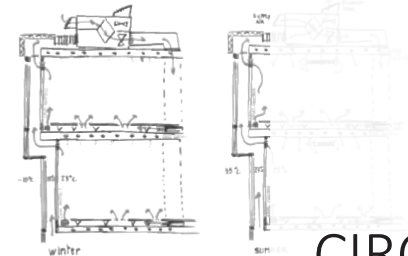

CIRCULAR ECONOMY IN CONSTRUCTION

DESIGN STRATEGIES FOR REVERSIBLE BUILDINGS

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BAMB BUILDINGS AS MATERIAL BANKS

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INTRODUCTION

Reversible Building is seen as a backbone of circular building and circular economy in construction. This publication explores a new perception of future buildings which are dynamic/reversible structures built with exchangeable modules and products for multiple use. A perception which sees a building not as a finished static product, but as an ever evolving structure which keeps up with the time, new technological developments and user requirements. A building which is upgradable and accommodates changing user needs and technologies over time. A building which is always fit for purpose while no m² of material is wasted during the transformation and upgrading processes and while each m² of material has valuable applications during its whole life (through multiple use options).

A new philosophy is being explored which entitles building waste as design mistake (Durmisevic 2016). The reader will explore directions that need to be taken in order to repair a fundamental mistake in existing building design and construction practice. This practice is defined by conventional design approach which does not extend beyond initial use life of buildings and materials. Such buildings are designed for one end of life option – demolition and down cycling. The publication will address strategies to achieve this paradigm shift and enable development of dynamic buildings with well-balanced interactions between durable and changeable building layers while creating a reversible monument of the future.

The publication will present and illustrate design strategies and technical solutions for realisation of such (circular) reversible buildings. It will also address key strategy for reversible refurbishment projects. Numerous design indicators, guidelines and principles will be highlighted and illustrated by BAMB pilot projects.

The publication will be published as E-Book and will be freely assessable to everyone interested in the new world of circularity of material resources through the build environment.

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BACKGROUND

In Europe, the building sector accounts for 38 percent of the total waste production, 40 percent of the carbon dioxide (CO_2) emissions and 50 percent of all natural resources used within construction (EIB 2015).

In addition, real-estate developers warn that the existing building stock does not match the ever increasing changes in market demand. For example, in the Netherlands, 8.5 million m^2 of office spaces are vacant (PBL, 2013). Fifty percent of investments in building construction in the Netherlands are spent on partial demolition and adaptation of the existing buildings and 42 percent of new construction is due to the replacement of demolished buildings which do not have the capacity to be modified to accommodate new needs.

In a time of diminishing resources and increasing environmental problems, it has become crucial to understand the capacities of buildings to transform a negative environmental impact into a positive one. The question is: How does one transform the current linear approach to the design of buildings that have one 'end-of-life' option (demolition) to a circular design solution that will guarantee multiple life options of the building, as well as its systems, products and materials? The switch is needed from a short-term focus on initial use requirements to a scenario which incorporates design visions for reuse of buildings and materials. Such an approach emphasizes the importance of reversibility of buildings and their structures. It focusses on disassembly, transformation and reuse as a means to bring the construction closer to the continual use loops of resources in its systems, products and materials. A world where buildings and materials are circulating in continuous reuse loops represent multiple value propositions and form a base for Circular Economy (CE) in the construction sector.

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REVERSIBLE BUILDINGS

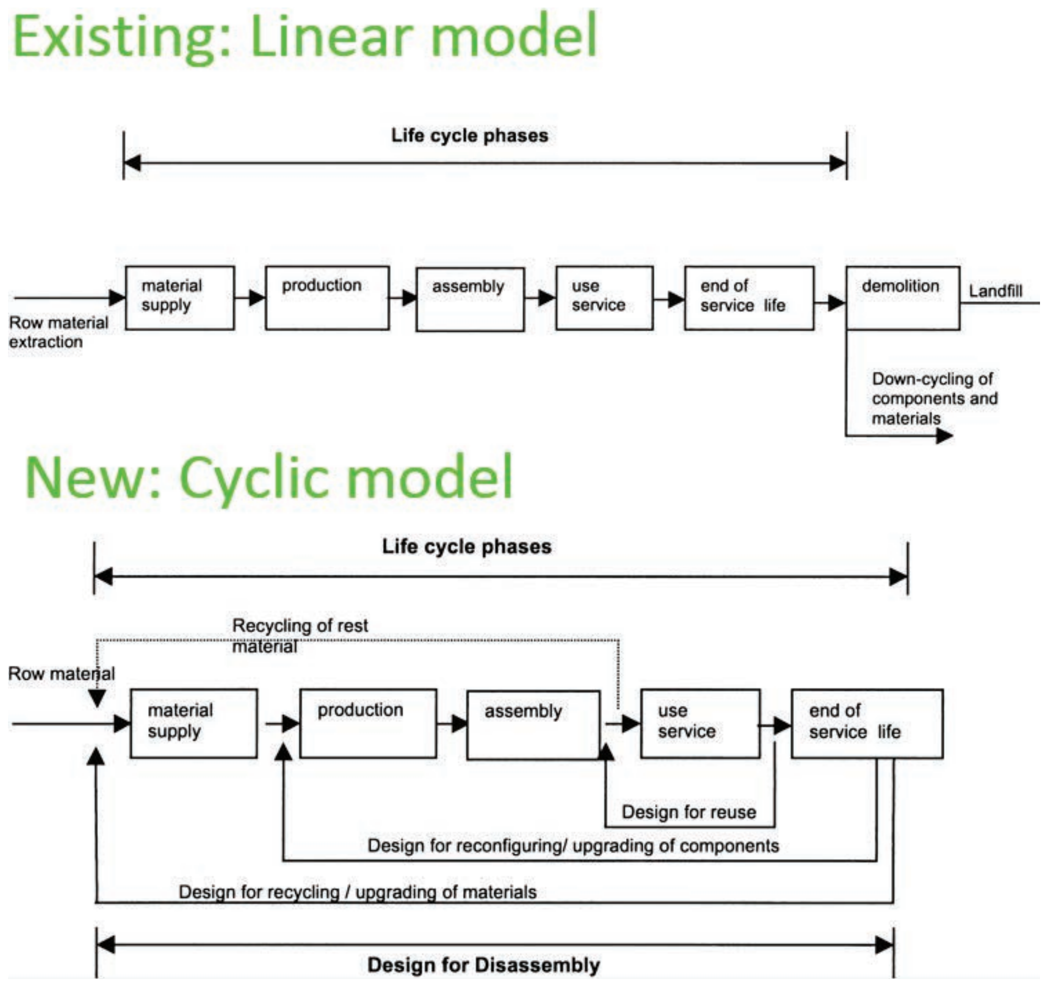

Figure 1 *Difference between linear model with focus on design for one end of life and circular model of material use in construction with focus on design for multiple life's and reuse options of materials (Durmisevic 2006)*

‘Reversibility’ is defined as a process of transforming buildings or dismantling its systems, products and elements without causing damage. Building design that can support such processes is reversible (circular) building design (RBD) and can be seen as key ‘accelerator’ of CE in construction.
RBD is therefore seen as a design that can take into account all life cycle phases of the building and focuses on their future use scenarios. However the focus of reversible building design within the BAMB project is on closing the shorter cycles of material recovery which have the most positive environmental and economic impacts. These cycles are presented in the figure 1

Design solutions that can guarantee high reuse potential of the building, systems, products and materials and that have high transformation potential are described as reversible. One example of such design solution is presented in figure 2. A key element of RBD is design for disassembly, which allows for easy modifications of spatial typologies and disassembly and high value reuse of building parts.

Numerous researchers as well as EU construction and demolition waste (CDW) reports, have indicated that the construction sector is confronted with crucial problem related to the huge amounts of CDW produced and the resulting loss of valuable resources. (ANNEX 1) WP3 state of the Art Report). BAMB Reversible Building Design research has identified fundamental system error embodied in the building design and linked the CDW directly to the design error, indicating that the way buildings are design determines life cycle of the building and martial stream in the future. (Durmisevic 2016)

In an ideal case, every molecule that enters a specific manufacturing process should leave as part of a saleable product; the materials and components in every product should be used to create another useful product at the end-of-life (Graedel and Allenby 1996) and the main structure of every building should accommodate different use patterns during its total life. Unlike car and product design where design for disassembly and design for reuse has been investigated and applied in the past, this approach is revolutionary to the building design.
Design for disassembly is defined as a characteristic of a product’s design that enables the product to be taken apart at the end of its useful life in such a way that it allows components and parts to be reused, recycled, recovered for energy or, in some other way, diverted from the waste stream . (ISO 14021:2016, 7.4.1)
Disassembly is a non-destructive taking apart of an assembled product into constituent materials or components (BS 8887-2:2009, 3.11)

On the other hand **demolition** in general can be defined as the process whereby the building is broken down, with little or no attempt to recover any of the constituent parts for reuse. (Crowther 1999) Most buildings are designed for such an end-of-life scenario since design for high recovery of building parts is traditionally not a part of design. They are designed for assembly but not for disassembly and recovery of building products, components and materials. On the contrary, they are integrated into one closed and dependent structure that does not allow alterations and disassembly. In addition, the materials used are often composites that pose a challenge to up/recycling processes. The inability to remove and exchange building systems and their products, components and materials results in: significant material consumption and waste; lack of spatial adaptability, e.g. modification of lay-out of the building; and poor technical serviceability of the building, e.g. maintenance and replaceability of worn out products, components and materials. (Durmisevic 2009)
Buildings are made of thousands of materials that have a technical life cycle from of 10 to 500 years or more e.g medieval brick and stone work. The *use* of these materials differs as well. The general static approach to building integration ignores that building systems, products, components and materials have different degrees of use and technical durability.

While the structure of the building may have the service life of up to 80-500 years, the cladding of the building may only last 20-50 years. Similarly, services may only be adequate for 15 years, and the interior fit-out may be changed as frequently as every three years. The first step towards managing the temporal tension in building

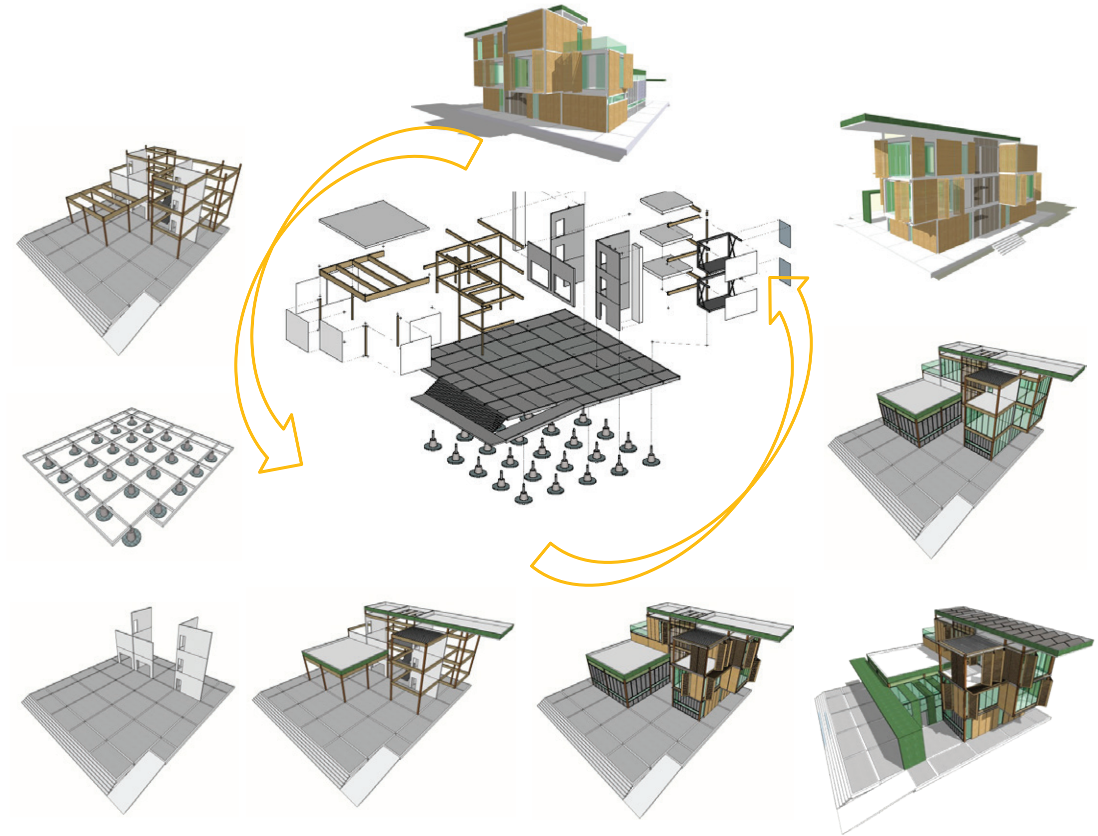

Figure 2 *Reversible Building with focus on high value recovery and reuse of building parts through design for reuse and reconfiguration. (Innovatie Catalogus 2017)*

is through decoupling the different levels into slow and fast changing time levels. (Figure 3)

Figure 3 illustrates different use durability rates of building components. In conventional building structures, faster-cycling components, e.g. space plan elements (see figure partitioning) are in conflict with slower-cycling components, such as the structure of the building, because of the permanent physical integration between different material layers with different use or technical life expectations.

The ultimate durability and circularity of buildings is not only related to the durability of its materials but more importantly to the way that the materials are put together.

The Reversible Building Design Tools and Protocol aim at raising the awareness, on a design table, about the impact of design decision on future waste creation and material consumption.

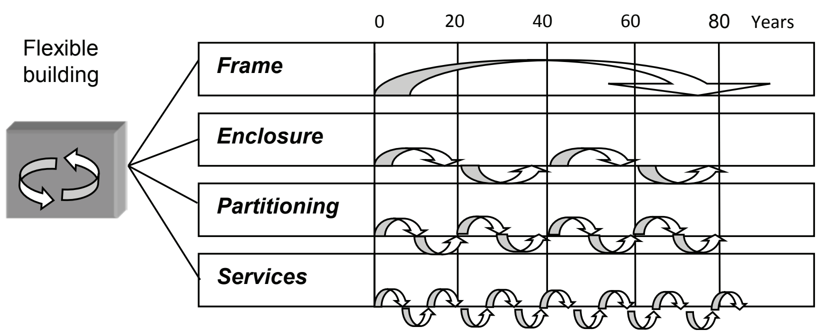

Figure 3 *Different durability rates of building components (Durmisevic 2006)*

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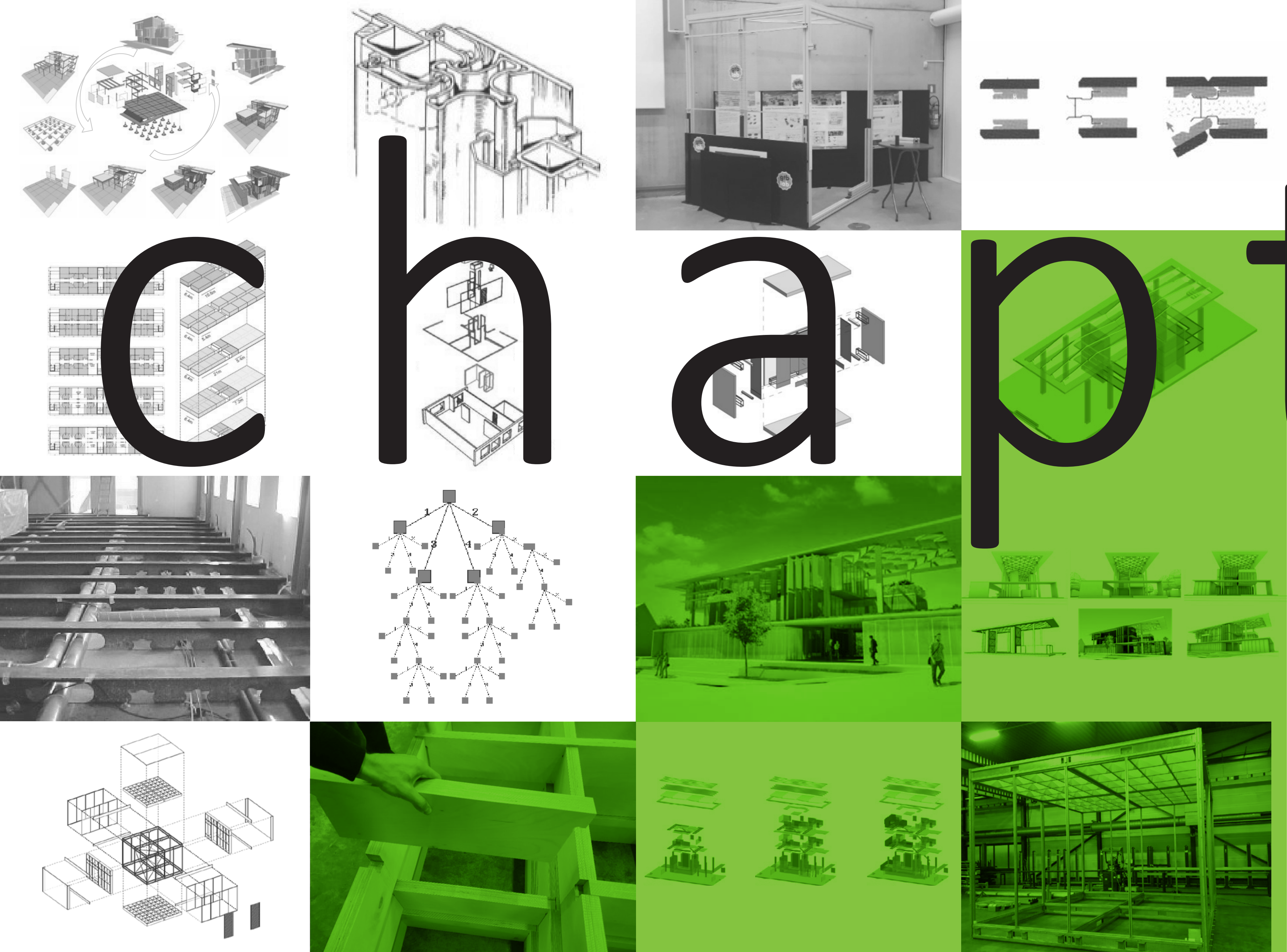

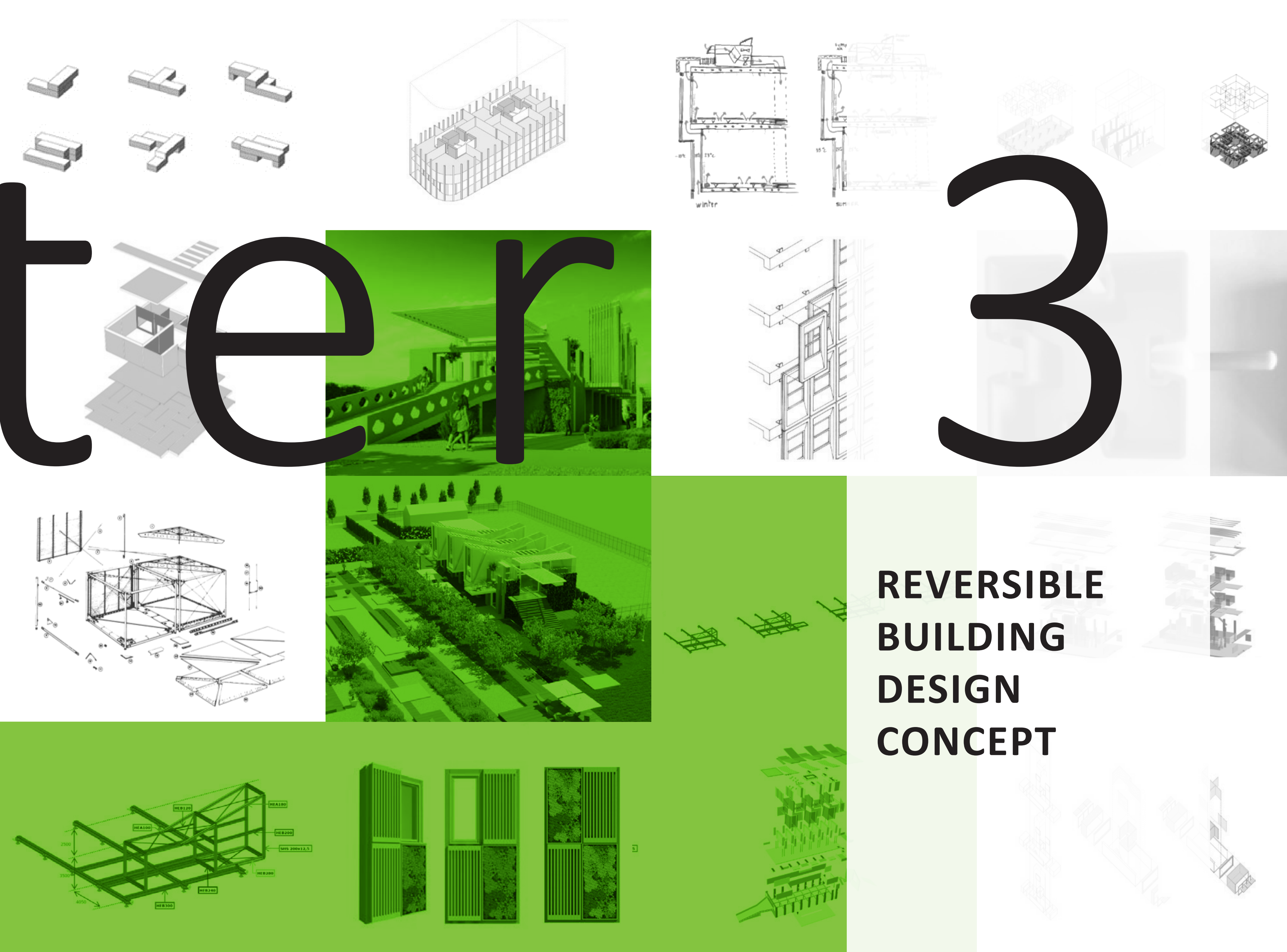

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REVERSIBLE BUILDING DESIGN CONCEPT

RBD can be seen as a new philosophy where demolition and the resulting waste are considered as a design error. The intention of RBD design is to design for circular value chains. This means that design should guarantee multiple reuse options of the building, its systems, products, components and materials and provide incentives to retain or increase building value through reuse, repair, reconfiguration or remanufacturing. Different scenarios for reuse and transformation of buildings, systems, products and materials will result into different business/ financial models which will reduce the risk of vacancy and poor technical performance in the future. Renting space is already a well-known concept in real-estate, but as a result of RBD, renting building systems, products, components and materials or their *performance* will introduce new business concepts (product service systems or take back systems).

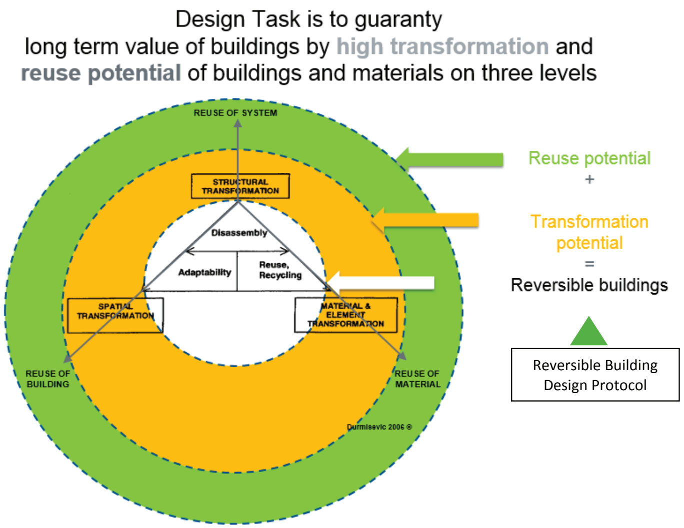


Figure 4 *three dimensions of transformation supported by reuse. Both reuse potential and transformation capacity are measures of the reversibility of a building. (Durmisevic 2006)*

When exploring the concept of Reversible Building Design, three dimensions of reversibility can be identified within a building, namely (1) spatial, (2) structural and (3) material reversibility. This concept is presented in the figure 4. Reversibility of these dimensions is accommodated by transformative actions such as the capacity to separate, eliminate, add, relocate and substitute elements of the system without demolition (Durmisevic 2006). As such, these dimensions determine the level of space transformation (first dimension), structural transformation (second dimension) and material transformation (third dimension). RBD tools are helping designer to understand the reversibility potential of their designs, manufacturers to develop reversible and circular products, owners to gain a better understanding of the whole life cycle asset value, contractors to develop reversible construction methods and demolition contractors to gain better understanding of the composition of buildings and their reuse potential.

If building design integrates all three dimensions of reversibility into the final design solution then the high value recovery can be expected on all three levels during the whole life cycle of the building and its systems and materials. RBD tools will enable the three dimensions of transformation within building (and associated benefits). Two key indicators of Reversible Building Design and dimensions of reversibility are the transformation capacity and reuse potential of building and its structure (on all levels building, system, product, element). Ultimately reversible Building is a result of high Reuse and Transformation potential of building. (Figure 4)

Both indicators depend on design for disassembly capacity and together (disassembly, transformation/ adaptability and reuse) form the nucleus of reversible buildings.

In that respect, design for disassembly can be seen as a key element of RBD, which allows for easy modifications of spatial typologies and high value recovery of building systems and components without damaging either. Furthermore, the assessment of disassembly aspects, which address both indicators of reversibility (1) adaptability and (2) reusability, contributes to the understanding of the level of reversibility of buildings. Low disassembly potential will result into low reversibility and other way around. (Figure 5)

Ultimately disassembly, adaptability and reuse form the nucleus of building reversibility and as such determine the level of spatial, structural and material dimensions of reversible buildings (Figure 4). Thus they can be mobilised to asses buildings but they can also be mobilised to guide design process towards more reversible solutions by becoming a part of Reversible Building Design Protocol. (Figure 5)

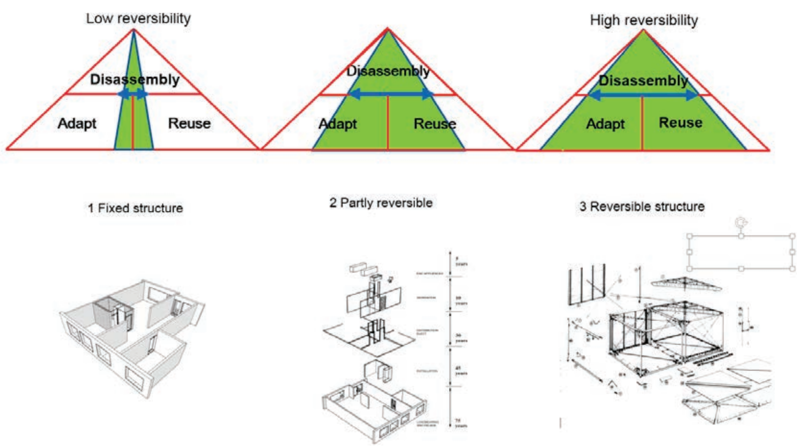


__Figure 5__ Key indicators forming a nucleus of reversible building design tools and protocol

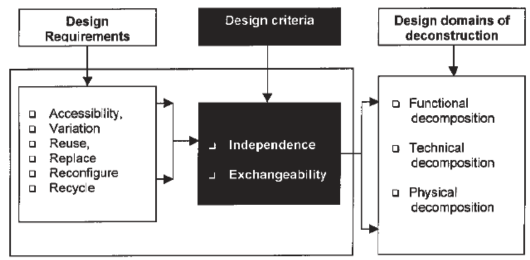
Furthermore, two key indicators of reversibility of building structure are Independence and exchangeability of building systems/components.

Independency addresses mainly functional independence and creates an environment in which assembly, transformation and disassembly of one functional cluster can be realized without affecting the other.

Exchangeability addresses technical and physical independence and creates the environment in which systems/components/elements can be disassembled without damaging surrounding parts of the structure and providing potential for their reuse in other context. Number and hierarchy of physical relations as well as interface typology that increases reuse potential are essential.

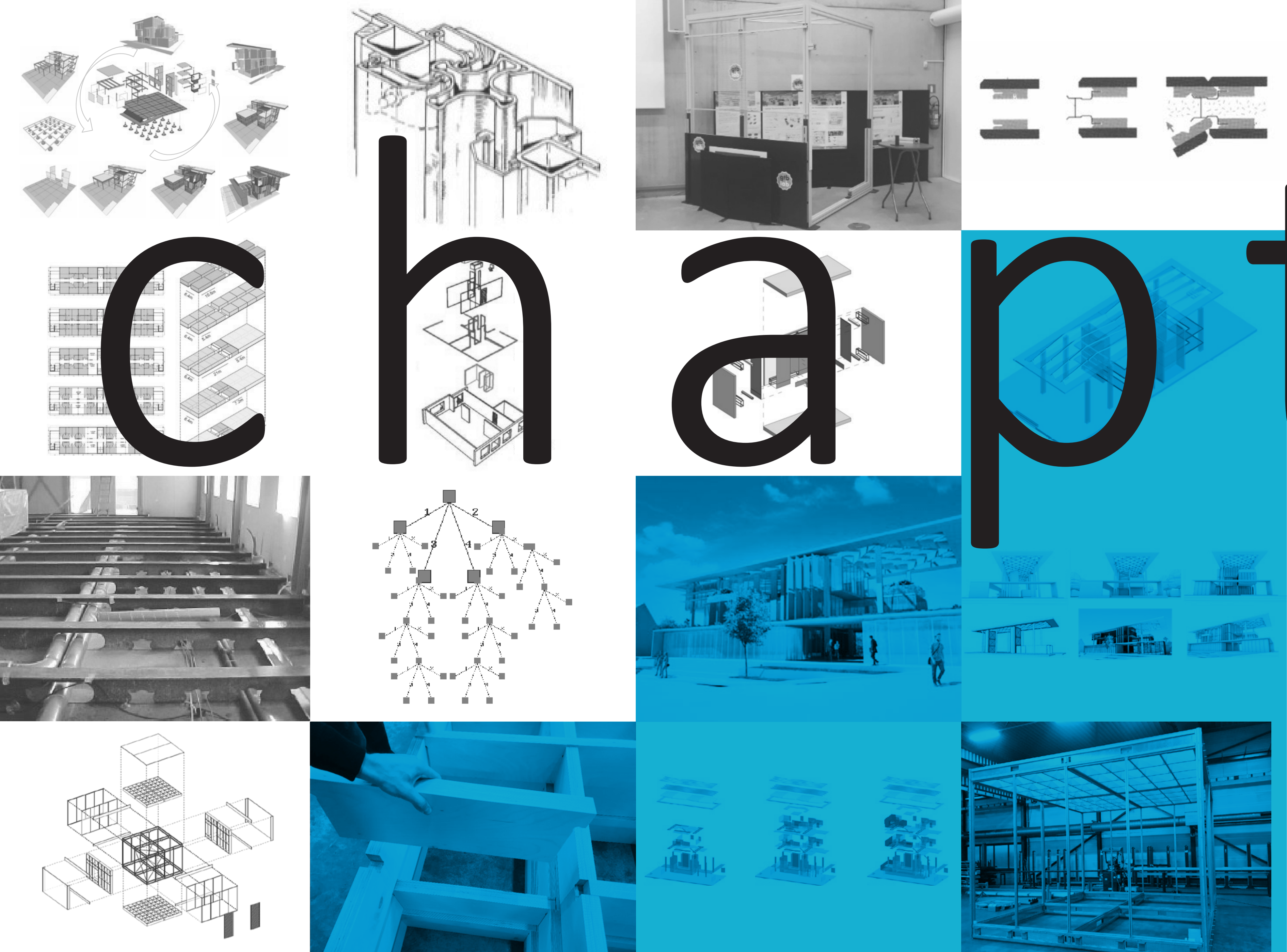
In order to design reversible structures that stimulate conscious handling of raw materials and provide high level of transformation and reuse, the following requirements should be fulfilled:

- Accessibility,
- Variation,
- Reuse,
- Replaceability and refurbishment
- Reconfiguration, and
- Recycling



A structure can be reversed if its elements/component/systems are defined as independent parts of a building structure, and if their interfaces are designed for exchangeability. Independence of parts is determined primarily by functional design domains, which deal with design of material levels of technical composition of building and specification of independent material clusters.

Exchangeability of parts is defined predominantly by technical and physical design domains that deal with hierarchical order of elements within structures, and with connections between elements.



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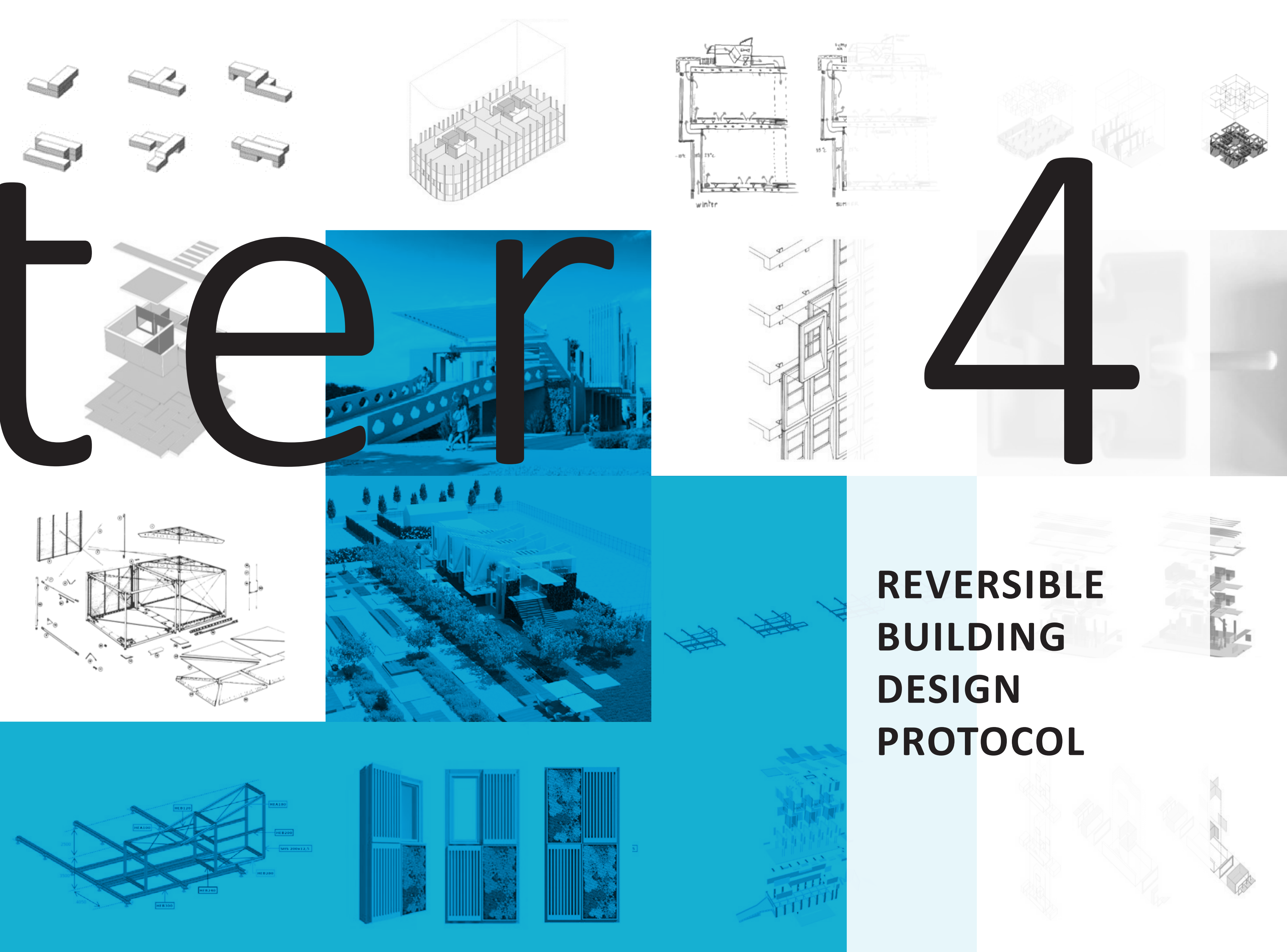

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REVERSIBLE BUILDING DESIGN PROTOCOL

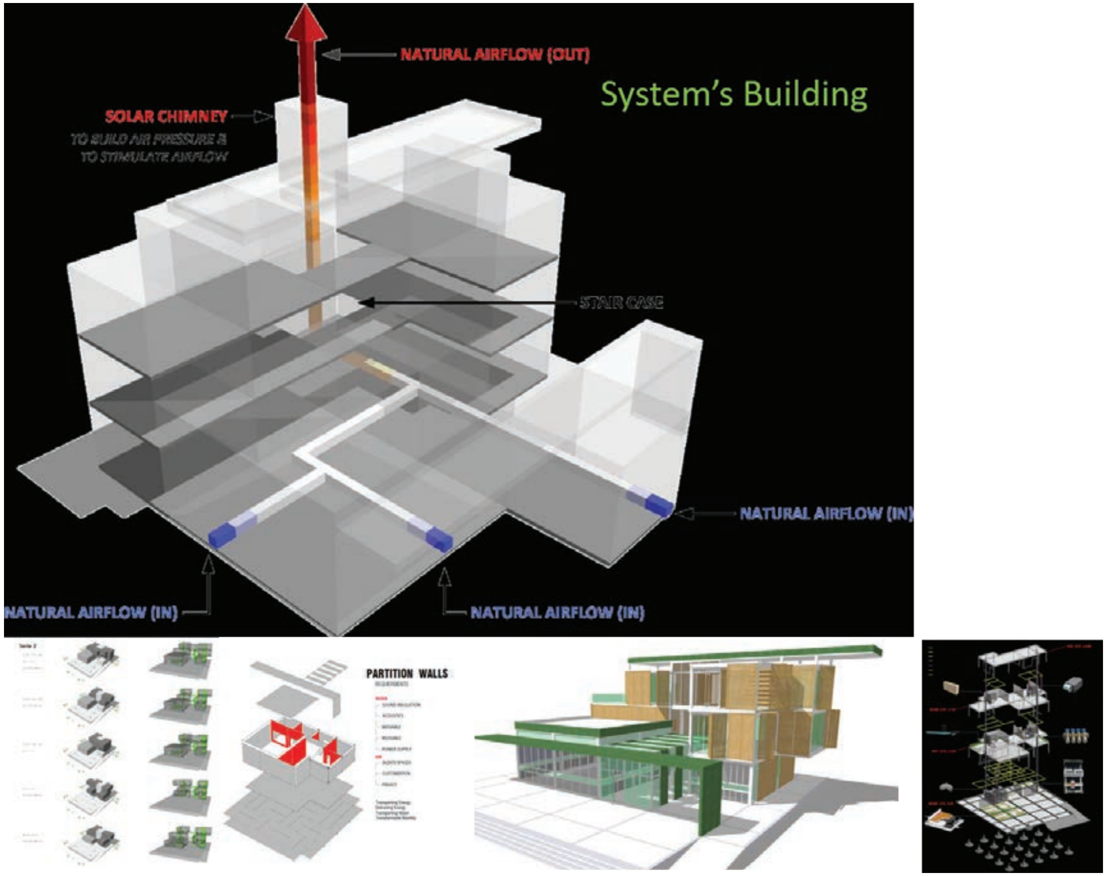


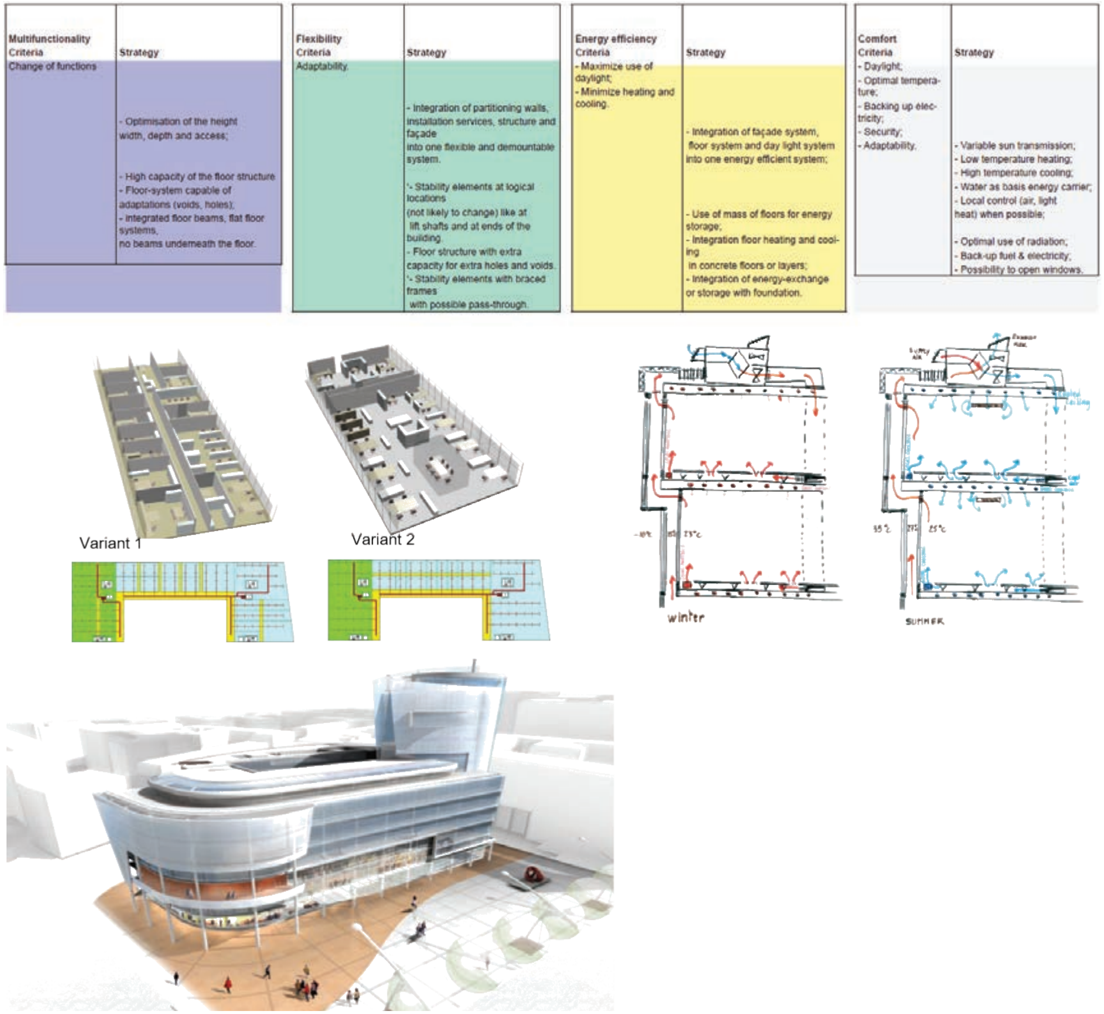
Figure 6 *illustrates new 4th dimension of key design parameters: space/function, structure/technique and esthetics/architectural language that forms Reversible Building through: dynamic space, dynamic structure, dynamic esthetics. (Results of international design studios University of Twente, University of Sarajevo, University of Istanbul)*

The Design Protocol for dynamic & circular buildings informs designers and decision makers about the transformation capacity and reuse potential of the design and the impacts of design solutions during the conceptual design phase. It aims to support the design of reversible buildings - and more specifically offices, apartments and public (socio/cultural) buildings with high transformation and reuse potential.

Reversible Building design extends the design scope beyond design of building that is materialized around one use program and one end of life option of its materials. A building, in general, is a complex system and is designed by optimizing three mayor subsystems functional, technical and esthetic subsystems. Reversible building design adds additional complexity to the design process by integrating factor time in the design brief which requires multiple use scenarios for building space and its materials. This requires more integrated systems approach to design. In place of isolating smaller and smaller parts of the subject being studied, systems approach works by extending its view to consider larger and large numbers of interactions as the issue is studied. Result of conventional architectural design is design of one spatial configuration supported by design of technical systems to support safe and comfortable use of space and esthetic appearance of architectural language. Reversible buildings consider not only one spatial organization but multiple options for use of space. Reversible building considers not only one specific purpose of used materials but considers multiple options for use of materials in the future. This means that the framework of reversible building design integrates additional dimensions to architectural design resulting into a dynamic architecture which considers spatial dynamics, technical dynamics and ultimately dynamic esthetics. (Figure 6)

The reversible building design process aims to result in the definition of a transformation model with defined boundaries which informs the owner, user what the designed building can do and what its capacity to change is. The core of the building (more permanent parts of the structure et. vertical loadbearing, communication and space for main technical services) dictates a transformation model and can be seen as a "hardware" which is often not fully visible in the building, but it determines whether the building can accommodate multiple functions and use scenarios through multiple use life cycles. One example of design requirements and integrated strategy for spatial reversibility which covers four main design aspects (multifunctionality, flexibility, energy efficiency and comfort) and its translation into a specific transformation model is presented in figure 7 through Design Criteria-Strategy Matrix and its integration into a design scheme.

With this in mind the main design question is how can the effect of total integration of different design aspects support the future transformation potential of a building



Multifunctionality Criteria	Strategy
Change of functions	- Optimisation of the height width, depth and access; - High capacity of the floor structure - Floor-system capable of adaptations (voids, holes); - integrated floor beams, flat floor systems, no beams underneath the floor.

Flexibility Criteria	Strategy
Adaptability.	- Integration of partitioning walls, installation services, structure and façade into one flexible and demountable system. '- Stability elements at logical locations (not likely to change) like at lift shafts and at ends of the building. - Floor structure with extra capacity for extra holes and voids. '- Stability elements with braced frames with possible pass-through.

Energy efficiency Criteria	Strategy
- Maximize use of daylight; - Minimize heating and cooling.	- Integration of façade system, floor system and day light system into one energy efficient system; - Use of mass of floors for energy storage; - Integration floor heating and cooling in concrete floors or layers; - Integration of energy-exchange or storage with foundation.

Comfort Criteria	Strategy
- Daylight; - Optimal temperature; - Backing up electricity; - Security; - Adaptability.	- Variable sun transmission; - Low temperature heating; - High temperature cooling; - Water as basis energy carrier; - Local control (air, light heat) when possible; - Optimal use of radiation; - Back-up fuel & electricity; - Possibility to open windows.

Figure 7 *concept scheme of multifunctional/flexible building shaped by high level of use of natural light and integration of energy positive and flexible loadbearing concept into a framework of spatial transformation. BBI center design 4D architects, Amsterdam 2002.*

and the reuse potential of its materials. In order to answer this question the design process needs to move from a linear and static approach to an integrated and reversible approach which is systemically addressing aspects of future potential through different design phases of the building. (Figure 8)

The Design protocol integrates the main criteria for the design of transformable buildings with reusable components into building transformation models and a set of design principles and design indicators pointing out the relevant design aspects and adequate design decisions for each design phase. RBD Protocol has been defined through five major steps:

1. Defining project objectives
2. Setting up Design Ecosystem for design of reversible / circular building
3. Design Brief
4. Design Process
5. MCDM (Multi Criteria Design Matrix)

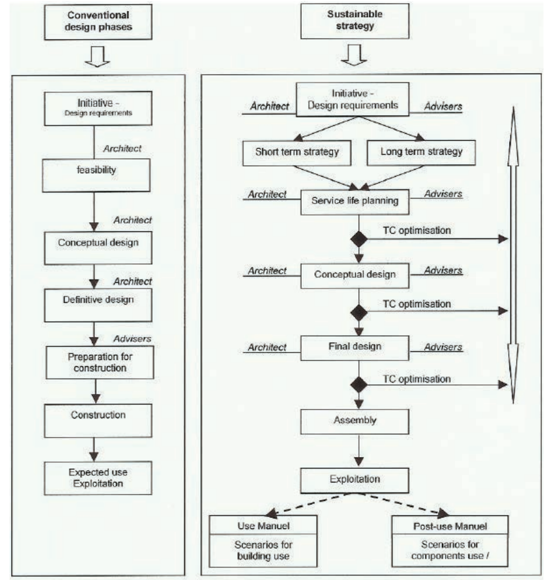


Figure 8 *left linear design approach right, RBD integrated design approach*

RBD PROJECT OBJECTIVES

4.1 DEFINING PROJECT OBJECTIVES

This initial stage needs to identify long-term strategies of the development through specifying short and long-term use scenarios. This will result into initial specification of different life cycle phases of the project and requirements needed per development/use phase. This will also trigger early considerations of financial and business models behind the development.

RBD DESIGN ECOSYSTEM

4.2 SETTING UP DESIGN ECOSYSTEM FOR DESIGN OF REVERSIBLE / CIRCULAR BUILDING

Design of Reversible Buildings has impact on multiple levels of decision making around design and construction of future-proof built environment, (form urban planning to logistics behind recovery of materials and business models behind creating material banks for new construction). Prior to start of design process of

Reversible Building relevant stakeholders and processes need to be put in place.

MUNICIPALITY

Involve municipality in the early stages of the project through the discussion about transformation options on the location (subject to the design) with respect to the future programming of that part of the city and potential diversity in functionality and size. These discussions will help define potential future use scenarios for the building as well as potential changes in number of users and size of the building. Number of users is affected by the capacity of the surrounding infrastructure to accommodate more people, provide parking spaces and services. This needs to be aligned with the potential future urban planning and strategies.

Since the societal needs and ideas about the space and quality of life are ever changing, buildings need to be designed in a way that will support these changes. They need to have capacity to accommodate these changes without demolition. Buildings which can do more than accommodate only one type of specific function and use capacity, will be used longer and will reduce the risk of having abandoned building in the future. Such transformable buildings can also be a key to vital sites. At the same time these buildings will also reduce needs for new buildings and building materials associated with new costs and energy/CO2 production.

BUSINESS MODELS

Investigate potential business models around the exploitation of the building and take into consideration potential business models/ take back systems for the major materials and services to be used.

Put processes in place that will ensure that each material used for the construction of the building is traceable and that protocol for preparation of take back contracts are prepared as a part of decision making check list during definitive design stage, so that mechanisms for ensuring second life of products and materials is set up front. This will set up decision making processes during design and construction phases so that building materials and services will have defined second life at the end of construction phase.

If existing Building:

APPLICATION OF TRANSFORMATION CAPACITY TOOL/ TRANSFORMATION CAPACITY REPORT

If a designer is involved in the reconstruction of the existing building or decision making whether to reuse parts of the building or not than Transformation Capacity of the building can be assessed through use of one of Reversible Building Design Tools "Transformation Capacity" tool developed within BAMB project.

Application of Reuse potential Tool/Reuse Potential Report

As mentioned above in a case of existing building and prior to making decision whether to remove the existing building or not design team should provide a report on transformation capacity of the existing building to accommodate new program. This report can be made by using Transformation Capacity tool which gives an indication of spatial reversibility and capacity to change functions and spatial typologies without much effort. See BAMB Transformation Capacity tool

If Transformation Capacity result is low (as result of TC assessment) than assessment of reuse potential report should be made using Reuse Potential Tool developed within BAMB. Reuse potential Tool will assess reuse potential of building products and material based on their material compositing and will specify the technical reversibility of the building in relation to the recovery level (unit, component, element, material). These results are then linked to the economic and environmental costs. Reuse Potential Report will identify which element of the building have a high recovery and reuse rate and can be part of a material bank for the new developments.

RBD DESIGN BRIEF

4.3 DESIGN BRIEF

Include potential future use scenarios for the buildings as well as for the materials, into the project requirements. Both will have impact to the further definition of user requirements and technical requirements within the project brief.

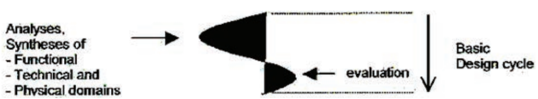


Figure 9 *Basic decision-making design loop*

USER REQUIREMENTS

User requirements part of the design brief needs to define future use options of the building.

The owner of the building needs to provide their vision and strategy for the long-term use of the building. As for example Housing project SOLIDS in Amsterdam has been designed with the capacity to accommodate housing but also offices and kindergarten, or a parking system in Luxemburg is developed with capacity to be used for housing and offices as well. Housing corporations might define the future use options and transformations of the building based on demographic studies, migration, future city planning etc. Business owners might define the future use and transformation based on the location and future changes in the neighbourhood, the predictions of business growth /decline, transformation of businesses, and future trends in work and work - living relation. Privat user might define the future use requirements based on its life style anticipating on future life phases (living as a couple, modifications to the extended family situation, modifications to housing for elderly etc). Definition of user requirements is one of the most important parts of design brief for reversible buildings since it will have direct impact on design of the volume and height of the buildings, design of the core which incorporates, structural stability, energy concept and vertical communication of the building and their capacity as well as on providing provisions to reconfigure or upgrade the core's capacity to support multiple transformations.

Different user requirements will further have impact on design of buildings technical configuration and its functional and technical decomposition levels.

TECHNICAL REQUIREMENTS

Technical Requirements part of the design brief needs to define future use options of the building structure. Scenarios for material circularity should be standard technical requirement in a design brief. This should require clear specification of materials in the building their properties and functionality as well as their future use options within a same functional application or potential to accommodate new function. The Design Brief should require delivery of final design accommodated with instructions for recovery of each product and number of recovery steps.

RBD DESIGN

4.4. DESIGN PROCESS

The task of the Reversible Building Design process is to give a form to a reversible building and its technical configuration defined by the level of transformation capacity as well as the independence and exchangeability of building products. In order to achieve this design process address two elements of Reversible Buildings (1)Spatial Reversibility and (2)Technical Reversibility. The way 4 indicators of spatial transformation have been addressed during design process and accordingly level of spatial and technical transformation has been defined will determine Spatial Reversibility and untimely transformation capacity of buildings (see BAMB Transformation Capacity tool).

On the other hand, design needs to address three domains of design of reversible structure: functional, technical, and physical design domains. The way 8 indictors of technical reversibility have been addressed during the design process and accordingly how functional, technical, and physical independence are achieved, will determent Technical Reversibility of building/ structure and ultimately Reuse Potential of Buildings and its products (see BAMB Reuse Potential Tool).

The 4 indicators of spatial transformation as well as the 8 indicators of technical reversibility are further detailed in the Reversible Building Design Guidelines in chapter 4.

A Reversible Building Design approach implies modelling of these aspects in an interactive manner through design. Reversible Building Design deals with many indicators and aspects that need to be analysed integrated and their solutions evaluated. RBD process therefore requires a structured process in order to be able to accomplish the goals. Therefore, system's design which deals effectively with ordering of complex decision-making processes provides a solid framework for implementation of Reversible Building Design process. The design process is an iterative process and has a number of decision-making loops which steers the design from feasibility analyses, conceptual design to final design and preparation for construction (including production/shop drawings) phases (Figure 10). Each of these general design phases are characterised by a number of iterative loops in search for the right match between spatial, functional and aesthetic aspect which will ultimately result into final design solution.

System's Design (or integrated design) consists of an orderly protocol that leads to the best decision for a given set of conditions. Due to its generic approach, it is applicable to all types and levels of buildings. When properly executed, system's design enables designers to obtain a clear understanding of the requirements for a proposed building/system and can help owners and designers to evaluate proposed designs and select the best or optimum design. In the line with system's design approach all RBD phases deal with three essential steps within each decision-making loop: Analyses, Synthase and Evaluation (Figure 9).

Analysis (indicate what the design is to accomplish)

Analysis includes identification of objectives and establishment of RB performance criteria for the building/product. In other words, the analysis phase deals with requirements specification. Requirements define a design problem and capture the key information needed to describe design decisions. The questions that are addressed during this phase with respect to RB are a the number and types of use options, respectively when and where will disassembly take place and which arrangement of components and connection design will enable transformation and recovery without demolition and loss of value.

SYNTHESIS

(formulation of a system that meets objectives and constraints).

Synthesis is the process of selecting desired aspects and solutions to form a building/product that meet design objectives. In the context of design for high Reversibility of Buildings, the Synthesis phase considers design principles that address four indicators of Spatial Reversibility and eight indicators of Technical Reversibility during building/system development and proposes the best solution. Reversible Building Design Guidelines lead designer to reach the best reversible solutions.

EVALUATION

(Evaluation of Reversible design solutions).

The evaluation aims to indicate the level of reversibility of a design solution. Its effectiveness can then be linked to environmental and economic impacts of the design solutions assessed by circular building assessment BAMB tool. The data obtained during an evaluation is used to perform improvements in the design through providing feedback information to the analysis and synthesis design steps. Evaluation can be done by use of assessment models for example Reversible Building Design Tools or by development of physical prototype of building parts and testing their effect on reversibility.

The level of reversibility, is measured by the BAMB

Transformation Capacity tool (TC) and Reuse Potential tool (RP). TC tool is predominantly used as evaluation through decision-making cycles of preliminary design and is further used through final design stage and preparation for construction design stages for the verification of the final Transformation Capacity index. (RP) Reuse Potential tool is used as evaluation tool through decision-making cycles of definitive design phase and is further used through preparation for construction phase for the verification of the final Reuse Potential index. Evaluations are done according to the criteria of spatial and technical reversibility described in D8 and D9.

These three steps analysis, synthesis and evaluation can be seen as elementary activities of a basic decision-making cycle.

In the beginning of a design process, basic loops are the largest, since all requirements are still not clearly defined, and many aspects need to be researched. If information about some aspects is lacking, the designer may proceed assuming a default value for the information. However, this decision is then regarded as tentative (Tichem 1997). After the missing information is generated, a tentative decision becomes a definitive decision. Within each new cycle, the process becomes more focused and project requirements more detailed, up to the point where the last unknown elements are defined. The design decision making cycle can be repeated any number of times during the design process, while moving the design from an abstract to an alternative and finally to a specific end solution.

Each design cycle deals with RBD aspects in an iterative manner, from provisional to detailed decision making cycles. From building level reversibility addressed during preliminary design to system and component level reversibility addressed during definitive and preparation for construction design stages. This process can be pictured as several design loops as shown in the Figure 10. These loops correspond to the decision-making cycles regarding the building level transformation and further on functional, technical, and physical independence on different levels of building technical composition.

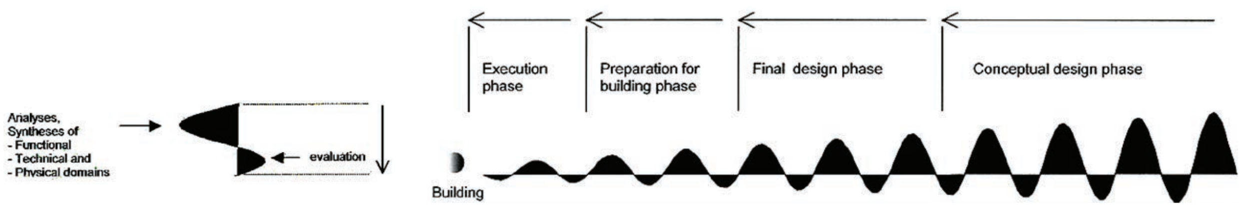


Figure 10 *design process as number of iterative decision-making loop containing analyses, syntheses and evaluation of design solution*

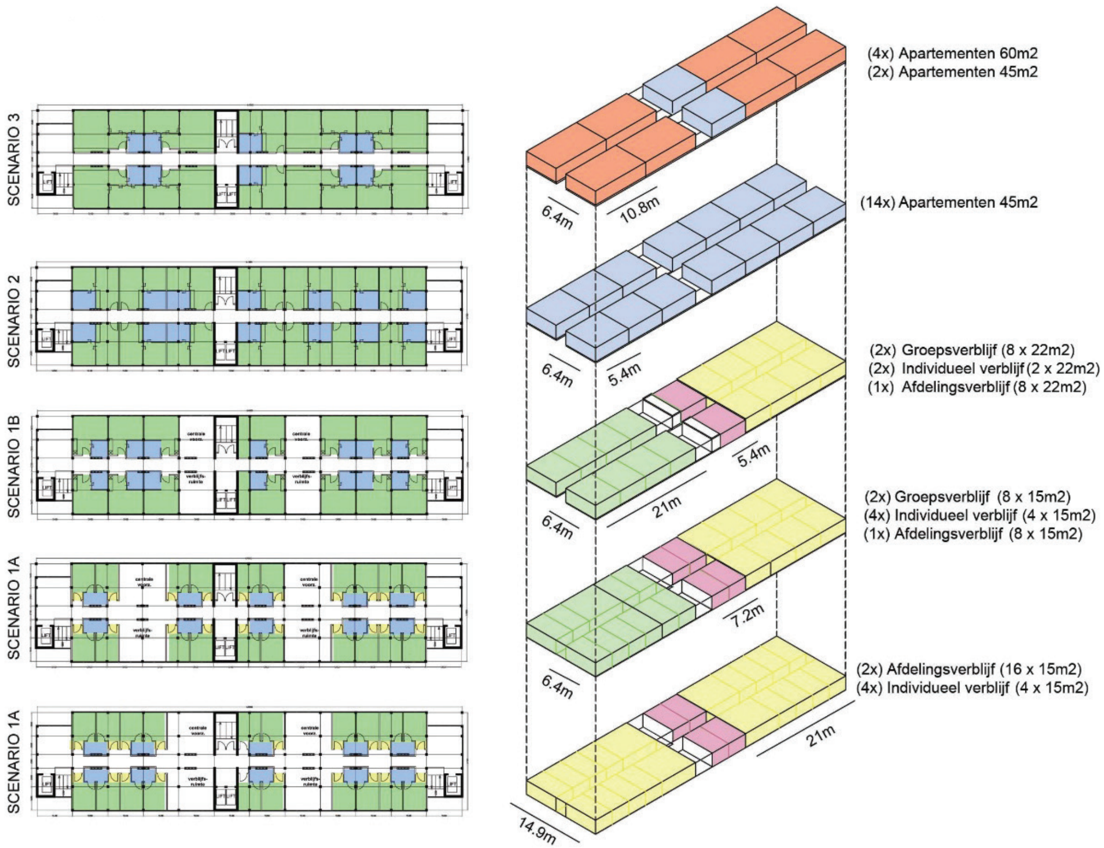


Figure 11 *Initial design phase/ feasibility study defining spatial reversibility and Transformation Capacity on building level indicating the compatibility of design solution with other desired use scenarios..*

Considering this, the basic RBD design cycle can be defined as:

1. Analysis of RBD requirements and/or analyses of the evaluation results and definition of requirements for the next design cycle.
2. Syntheses: design of reversible building and improvements of the RBD aspects in order to increase reversibility of design solution and associated building transformation capacity and reuse potential of building and its products/ materials.
3. Evaluation of the improved solutions of the Reversible Building and assessment of the TC and RP based on proposed design solutions from syntheses phase.

CONCEPTUAL DESIGN STAGE

During initial conceptual design aspect related to the spatial configuration, typology and dimensions as well as position and capacity of the core (stability, main installation net and vertical communication) are predominantly address (Figure 11).

During this phase reversible design guidelines (see chapter 5 and 6) and Virtual simulator inform designer about the spatial capacity of proposed spatial configuration to accommodate multiple scenarios. During the preliminary design phase, the focus of design lays on the functionality of the design object. Functional decomposition is therefore also partly addressed during preliminary design phase, manly indicating level of separation between main building functions on building level.

DEFINITIVE DESIGN STAGE

The functional decomposition is an important design indicator of technical reversibity which is further adressed through the final design stage. The second important reversible building design aspect in this stage is systematisation. Systematisation stands for the basic clustering of materials in order to perform a certain function. Which functions are clustered together,

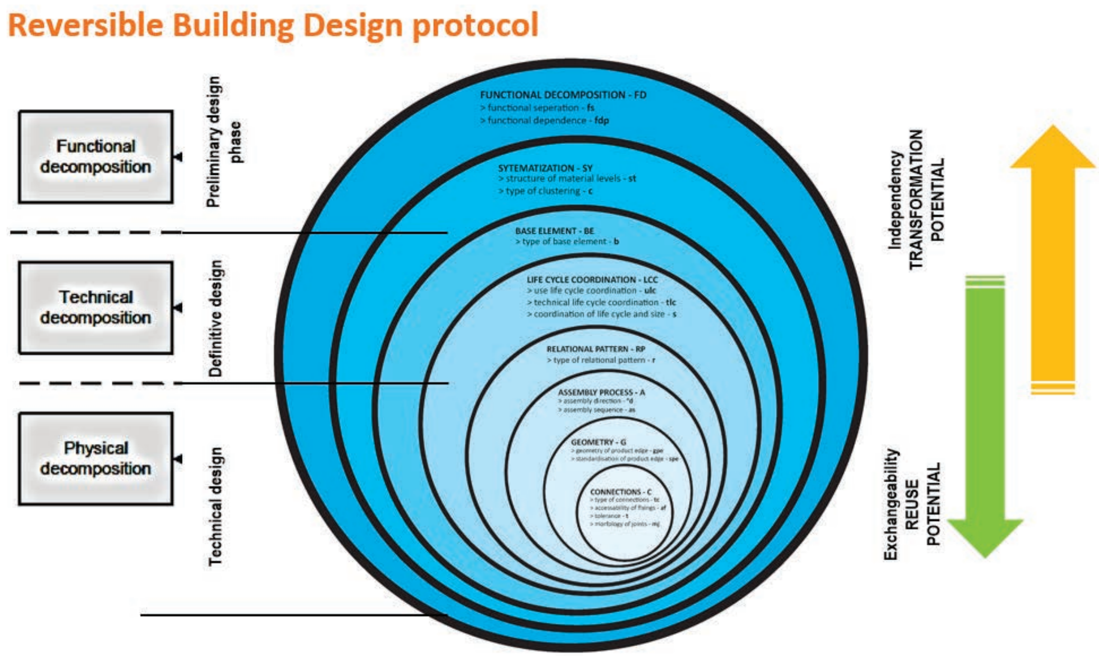


Figure 12 *indicators of technical reversible of building/product structure addressed through the different design stages.*

and which are not, will determine the product's reconfiguration options and complexity of technical compositing on building and product level.
Furthermore, the life cycle coordination of use and technical life cycles play an important role in providing more reversible solutions. The relations and relational patterns representing level of technical independece between elements and components also play a role in reversible solutions. These design aspects are prleiminay adressed during Definitive design stage. The physlical independece, which is defined by the connection types and geometry of product edge, is addressed on a principle level only and will further developed during preparation for constrution stage.

PREPARTION FOR CONSTRUCTION STAGE

During preparation for constrution physical independence is definilty set through the collabration with the manufature and design /engineering team. Definitive assembly sequences, geometry of product edge, tolerances and the typlogy of connections will ultimately determine disasmebly potential and the level of damage of recovered building products and materials.

If a design brief places more focus on transformation, than spatial trasformation, functional decompositon and technical decomposition would be a greater priority. If a design brief focuses more on high value recovery and direct reuse of single parts, than physical decomposition will be of greater significance. (figure 12) However, ultimately, if a designer is designing a reversible building, it is important to focuss with equal importance on spatial revreisbility, and the technical reverisbility, defined by all three levels of decomposition (functional, technical and physical).

During design process indicators of reversibility are used as design aspects. At the end of a design phase design solution is assessed using Reuse potential tool which has integrated reversible building design indicators as criteria for evaluation.

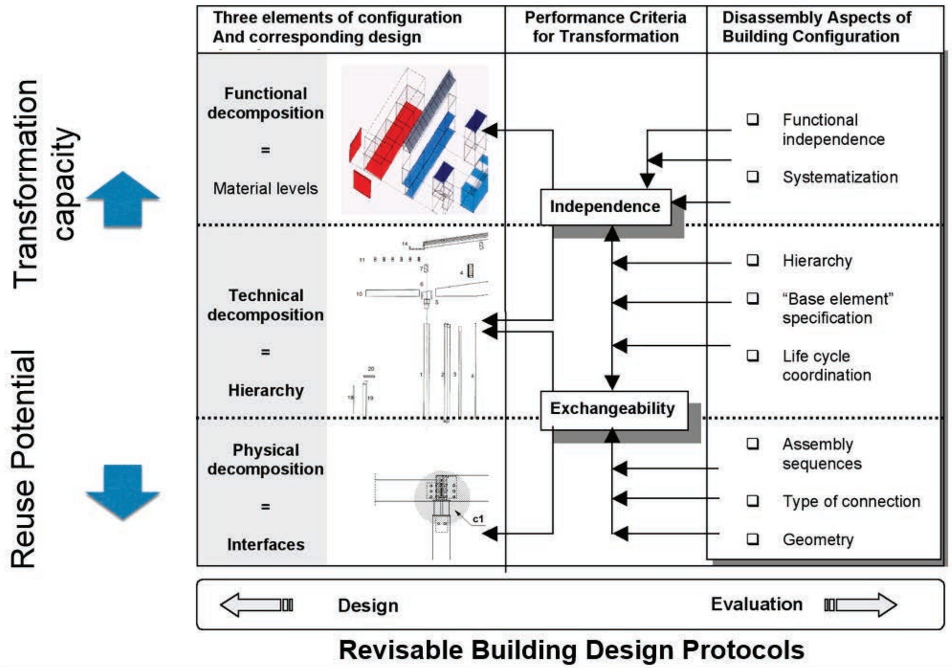


Figure 13 *Integration between RBD tools and design protocol during design/evaluation of building/product structure*

INTEGRATED RBD PROTOCOL

The Integrated Design protocol brings together aspects of spatial and technical reversibility (figure 14). Aspects defining the level of spatial transformation are researched during the preliminary design phase and are being further defined during the definitive design phase. Reversible building design tools and guidelines will inform the design process about important design indicators and aspects of design of reversible/circular buildings and its product. The use of the tools will shift along the design process. During the initial design phase reversible design guidelines and Virtual simulator will be used to inform designer about the key indicators of spatial reversibility and provide a feedback on initial design solutions.

As the design progresses through conceptual design phase, the transformation capacity tool is added to assess transformation capacity of design solutions.

During final design stage the focus will lay on use of design guidelines for technical reversibility in combination with reuse potential tool.

Table below illustrates when different RBD indicators are addressed through different design stages and supported by BAMB RBD tools.

Design Phase	Reversibility indicators	RBD aspects to be addressed	RBD tool
Preliminary design			
	block dimension in relation to the natural light	Block dimension ensures for possible subdivision and functional change to provide more use/letting options.	Virtual simulator
	Block dimension in relation to Hight	Block dimension is compatible with floor to ceiling height, window openings and visual comfort and health related to natural light and natural ventilation	Virtual simulator
	position and capacity core	Typology, position and capacity of the cores of the building (formed by structural stability elements, installation services and its main distribution, vertical and horizontal communication zones) ensures for possible subdivision and functional change and is compatible with fire regulations having in mined distance and dimension between fire compartments and of escape routing.	Virtual simulator
	dimension, typology structure	Type of structural system and span dimensions support multiple use options of space	Virtual simulator
	position capacity main installation net	Positioning and dimensioning of the main installation net and distribution installation net that will not form a barrier to future spatial	TC
	position /accessibility installations	Functional separation or planned integration between installation service zones and other functions of building structure as support, envelope/ enclose, space partition elements and space finishing elements to allow easy modifications to installation cervices without	TC
	independence	Separation / independence of main functions within building structure to allow for individual changes and modifications	TC
	Capacity/position	Position and capacity of the core of the loadbearing structure in a way that will not form a barrier to the future changes	TC
	systematisation	Clustering and positioning of the fixed parts of the building structure as stability elements, vertical loadbearing elements, main installation net (vertical) installation ducts, vertical communication elements, in a way that will not form a barrier to the future changes	TC
	separation/independent	Separation of installation distributing net and other functions of the units system that will allow easy relocation of walls, kitchen appliances, and installations that are accommodation space through the walls, floors or ceilings	TC
Final Design phase			
	independence	Building products and their parts which have different functions as well as different use and technical life cycle are defined as independent from each other and can be recovered without damaging surrounding	TC/RP
	Hierarchy	arrangement of components and hierarchy which enables open assembly and minimises constructing sequence	RP
	life cycle coordination(LCC)	Building parts are clustered according to their functionality, assembly, disassembly steps and life cycle coordination into pre assemblies and assembled as a prefab cluster on the building site.	RP
	life cycle coordination	Life cycle coordination is considered for the purpose of maintenance and transformation phases (elements with longer life span are not assembled in front of elements with shorter life span)	RP
	connecting type	Ideally elements are connected via Intermediary connection which allow disassembly of one parts without affecting the others	RP
	connection	Design support standardization of connections	RP
	Geometry	Geometry of product edge support easy disassembly without damaging the component and can withstand multiple assembly / disassembly sequences without damage	RP
	Connections/geometry	Connections are designed in such way that multiple reuse sequences will not weaken reusable element	RP
	independence / hierarchy/LCC	product can be reconfigured in order to answer new performance requirement independent, without damaging its parts	RP
Preparation for construction			
	systematisation	Building products and their parts which have different functions as well as different use and technical life cycle are defined as independent building clusters / products which can be prefabricated offsite	RP
	Hierarchy	setting up final arrangement of components and hierarchy which enables open assembly and minimises constructing sequence	RP
	life cycle coordination	Life cycle coordination is considered for the purpose of maintenance and transformation phases (elements with longer life span are not assembled in front of elements with shorter life span)	RP
	connecting type	During preparation for construction phase detailed connection design is verified and made compatible with production technique. Ideally elements are connected via Intermediary connection which allow disassembly of one parts without affecting the others	RP
	connection	During the preparation for construction stage all measurements need to be verified and optimised to a minimum nr of different connection types. Reversible Design support standardization of connections	RP
	Connections/geometry	Geometry of product edge support easy disassembly without damaging the component and can withstand multiple assembly / disassembly sequences without damage. Connections are designed in such way that multiple reuse sequences will not weaken reusable element. Final production geometry and connation design needs to be verified.	RP
	independence / hierarchy/LCC	product can be reconfigured in order to answer new performance requirement independently, without damaging its parts	RP

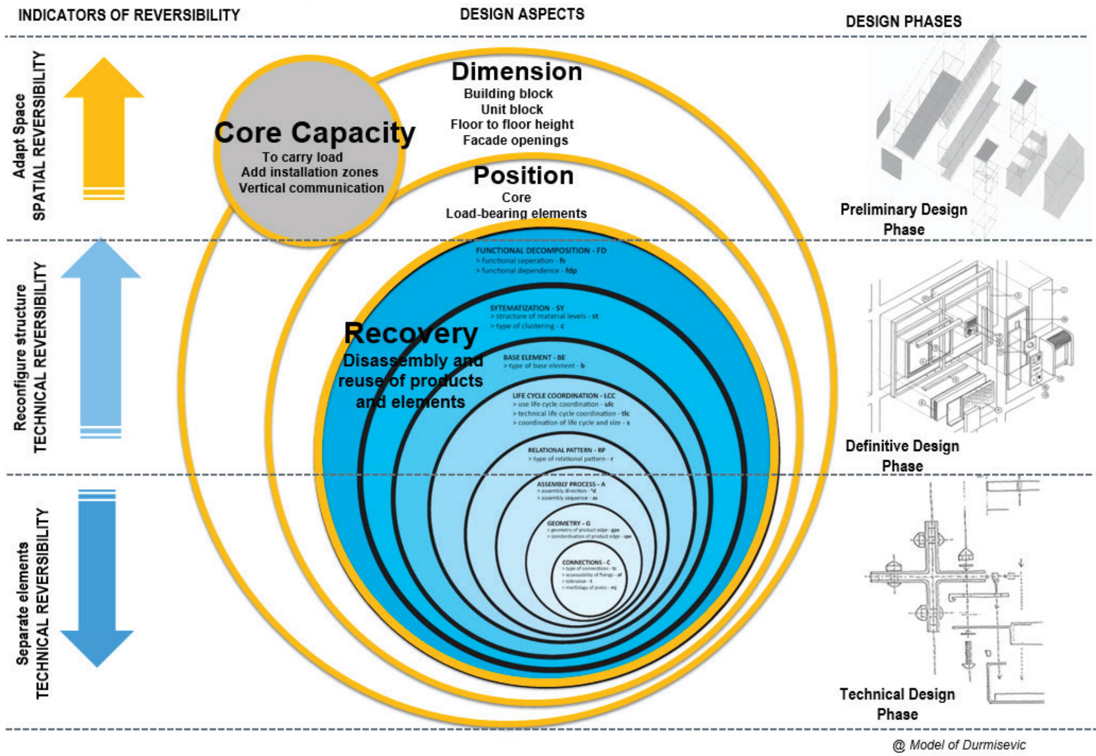


Figure 14 *Reversible building protocol integrating spatial and technical aspects of reversibility.*

RBD MCDM

4.5 MULTI CRITERIA DESIGN MATRIX (MCDM)

In order to progress towards a reversible/circular approach in building and construction, the design focus must go beyond the construction phase of building (which deals with optimization of cost, quality and time) to incorporate long-term operational phases, as well as the transformation, deconstruction and reuse phase. Conventional design focus was predominantly on optimization of short-term values as construction cost, quality, and time. Contrary to this, the circular/reversible approach to building design and construction treats these traditional competitive factors as sub-factors that are part of a long term sustainability strategy and considers building and its materials as long term socio-economic and environmental assets. (Figure 15)

In order to have a total view on the design aspects

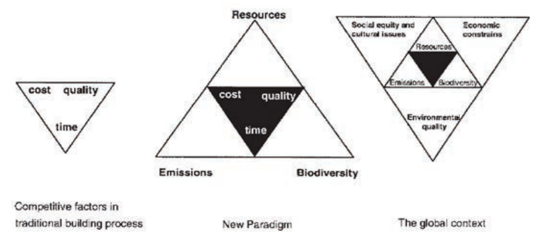


Figure 15 *transition of design focus from traditional comitative factors in the past (traditionally companies were competing in their bids based on three competitive factors costs, quality, time) to more environmental focus in 90's and going further to optimisation of a broader holistic scope which is shaping circular economy*

MCDM		**criteria and importance**	
Project: Reversible Urban Pixel			
By: Elma Durmisevic			**march 2017**
Deasign Aspects	**weight**	**CRITERIA**	**weight**
Architectural quality	10	identity	10
		scale/proportion	9
		integrity/coherence	9
		inviting building	8
		expression of reversibility	9
		appearance of spatial adaptation experiment	7
Spatial Reversibility	9	spatial capacity (adoptability to different functions)	10
		installation capacity	3
		loadbearing capacity for extandability	8
		possibility to install equipment	7
		suitability for the internal flexibility	8
		safety /security (fire safety)	9
		multifunctionality	8
Transformability	10	easy transformation from one use concept to another	10
		reconfigurable building systems	9
		extendibility / shrinking of space	8
		multiple reuse scenarios of elements	10
		adaptability to the weather conditions and day-night configuration	9
		reliability of the integration/connection between components	9
		adaptability to different inner climate concepts	7
		decoupling and reassembly of parts / units of the building with different funct	10
		flexible integration of systems (building and HVAC)	7
energy, water, materials	9	stimulus for low energy user behaviour	8
		renewable energy / renewable	9
		direct reuse of elements,	10
materials		reuse by adjustment,	8
		C2C	8
		re-usability of disassembled components	10
water		reuse of different water streams	8
Comfort and health	8	thermal comfort (winter)	10
		thermal comfort (summer)	10
		indoor air quality	10
		ease of usability of the structure and spaces	8
		visual comfort	9
constructability, and handling of components	9	high level of industrialisation/prefabrication for fast assembly,dissasembly	10
		easy to assemble, disassemble and reassembly	10
		transportability of the components/systems	9
		easy to store	8
		easy reconfiguration of prefabricated components for reuse	9
		transportability of the components/systems	8
cultural and local site context	8	integration of cultural behaviour aspects to the design	8
		integration of cultural aesthetic qualities	8
		local climate conditions	10
Cost	7	Investment cost	8
		Annual exploitation cost	10
		life cycle costs	10

Figure 16 *Multi Criteria Design Matrix for design of reversible buildings specifying design aspects and project priorities and ambition*

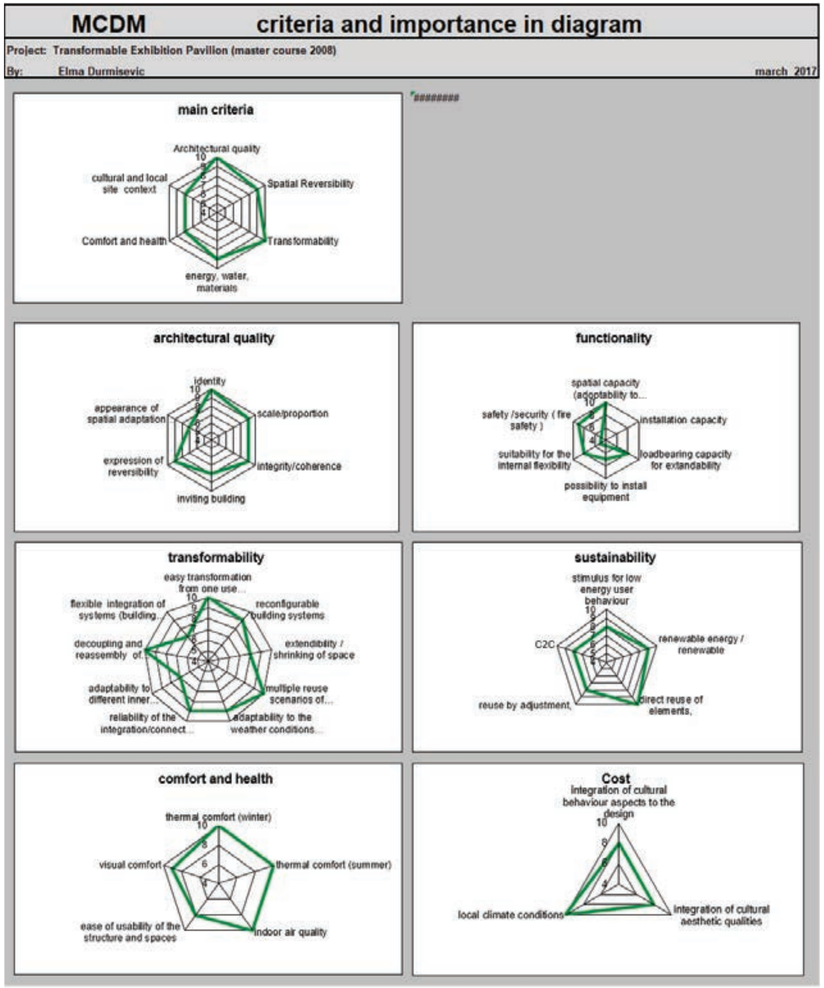
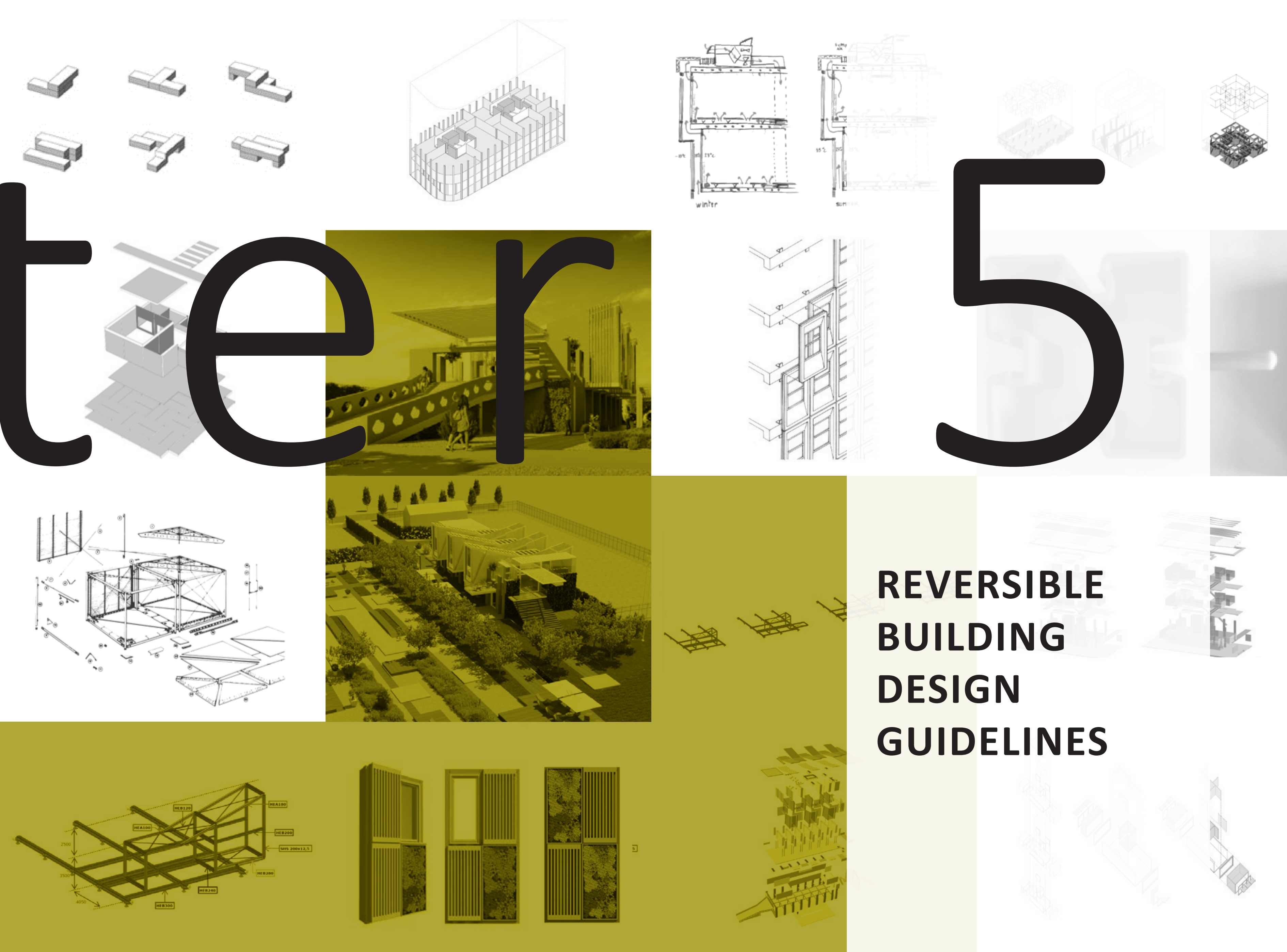


Figure 17 *graph representation of MCDM aspects and ranking of their aspects through International Design Studios (IDS 2018)*

and performance of proposed design results RBD aspects are integrated into Integral Multicriteria Design Matrix moving beyond conventional competitive factors and incorporation Reversible Building Design aspects in a total profile of designed buildings which consider architectural quality, spatial functionality and transformability, comfort, energy performance, quality of materials, constructability, social and cultural issues and costs. The integration of spatial and technical indicators of Reversible Buildings into the design process has been analysed during 5 International design studios that took place in 2016,2017 and 2018 with in total 90 students.

MCDM defines and visualises an ambition of the building project and helps creating a common understanding between the owner and the design and engineering team on the ambition and priorities in the project (Figure 16 an 17). MCDM is a communication tool between the client and the design and engineering team and forms a base line at the beginning of design process visualising design brief/ requirements. Further to than MCDM is made at the end of each design phase in order to communicate the difference between desired performance of the building which has been set up at the start of the project and design solutions being presented and discussed during each design phase. MCDM is also a designer's check list which keeps the internal evaluation process on track.(Figure 16)

chap



ter 5

REVERSIBLE BUILDING DESIGN GUIDELINES

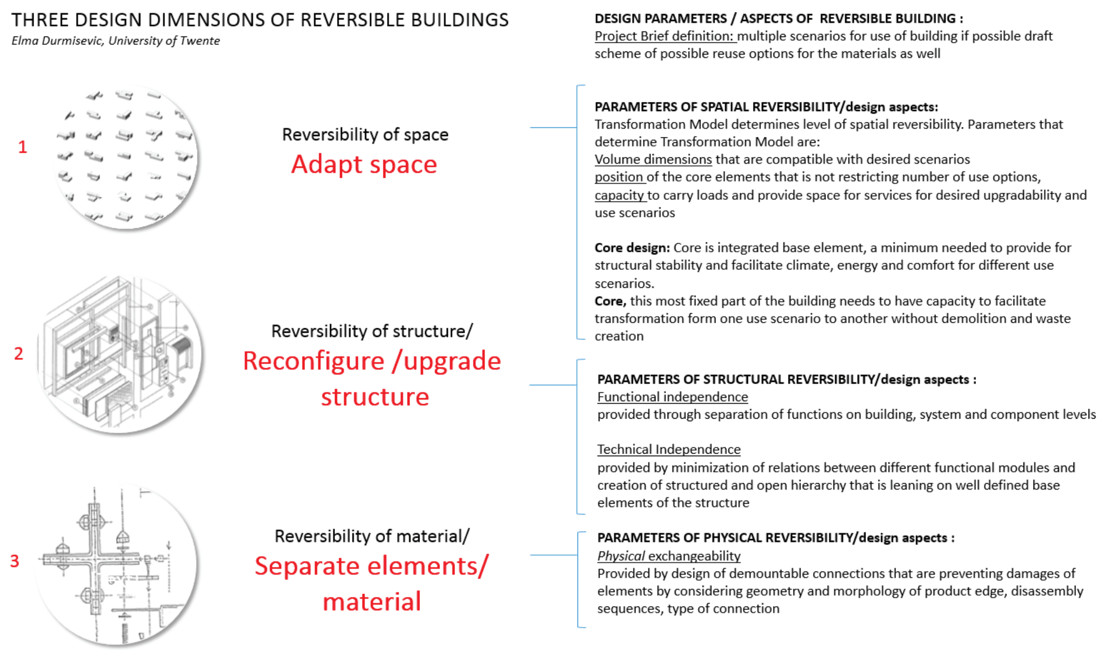


Figure 18 *three dimensions of reversible buildings*

Emphasizing the ability of buildings and their components to return to an earlier state, RBD strategy strives for high resource productivity. It includes a spatial dimension, in which the building can be efficiently transformed to meet new spatial requirements, as well as a technical dimension, wherein the buildings components can be refurbished, disassembled and used again or deconstructed and recycled or biodegraded. When exploring the concept of circular buildings and circularity of material streams through all life cycle phases of the building and its parts three dimensions of transformations within the building are being highlighted, aiming for a high-quality recovery of the building and its constitutive parts. Those are Spatial, Structural and Material dimensions of transformation. (Figure 18) They have an impact on all physical levels as the building, system, and material level. The reversibility of these levels is accommodated by transformation actions as;

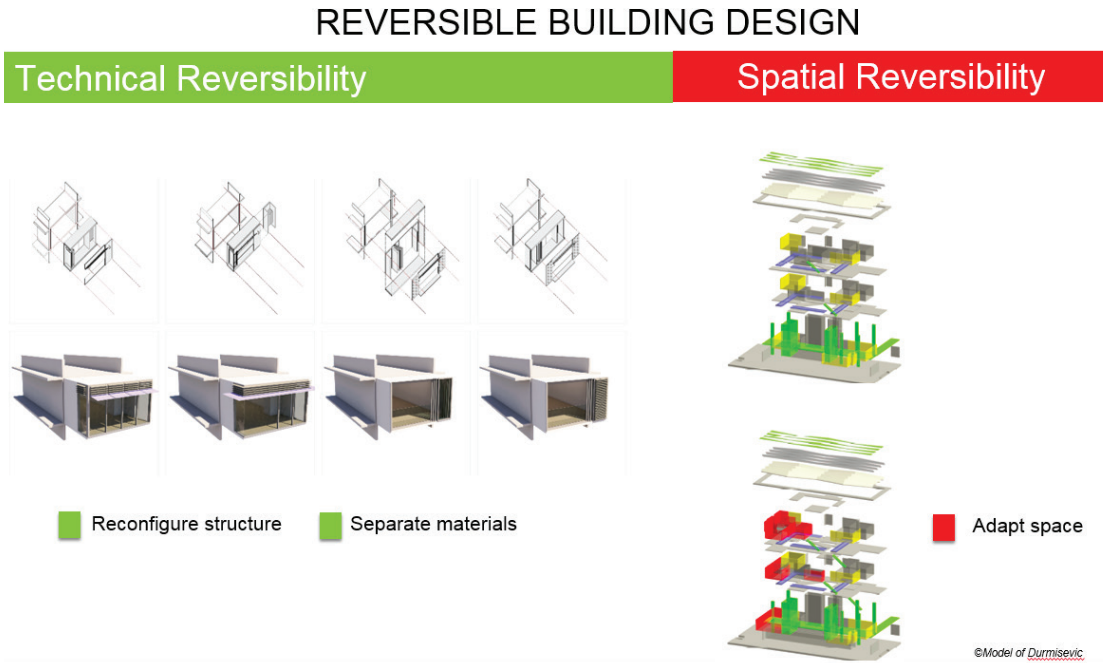


***Figure 19** Two categories of reversibility which address three design dimensions of reversible building design Spatial, structural and material (Durmisevic 2016)*

the separation, elimination, addition, relocation, and substitution of parts and as such determine the level of spacial transformation, structural transformation and material transformation. Dominant agent of such three-dimensional transformation on all building levels of building is the capacity of the building structure to transform and enable reuse of its parts.

The guidelines in this document address two main pillars of reversible buildings presented in Figure 19. Those are Spatial reversibility, (addressing transformation on building level) and Technical reversibility which covers structural and material dimension of reversibility(through analyses of functional indecency of building products, their hierarchical arrangement and connections within building structures).

Spatial and Technical reversibility are the two main categories of reversibility of buildings. As explained in previous text these design dimensions are supported by the nucleus of reversible building design formed by disassembly, adaptability and reuse. (figure 5)

The framework of Reversible Building Design guidelines has been built based on the main reuse and transformation criteria and their interactions, interdependences and importance. 4 key design criteria defining spatial reversibility and 8 Key design criteria defining technical reversibility have been identified:

Spatial reversibility:

1. dimension (building level)
2. position of core elements
3. building level Disassembly
4. capacity of the core

Technical reversibility

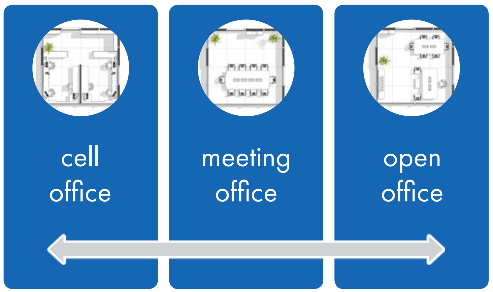
1. functional decomposition
2. systematisation and clustering
3. hierarchical relations between elements
4. base element specification
5. assembly sequences
6. interface geometry
7. type of the connections
8. life cycle co-ordination in assembly/disassembly

5.1 SPATIAL REVERSIBILITY

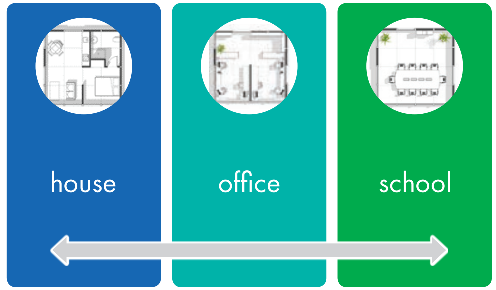
Figure 20 *Three Categories of transformable buildings with three levels of spatial reversibility*

Spatial and building related transformation (change of the building function and its impact on the building structure) are analyzed during the feasibility and preliminary design phase. The analysis focusses on the capacity of space and structure to accommodate different functions without causing major reconstruction works, demolition and material loss. The less effort is needed to transform a building, the higher the transformation potential will be. The greater the variety and number of modification options (reuse options of buildings), the higher the transformation potential. The three major types of transformations are identified as: mono functional transformation options, trans-functional transformation options, and multidimensional transformation which integrates the above two as well as exchangeability and relocation. (Figure 20)

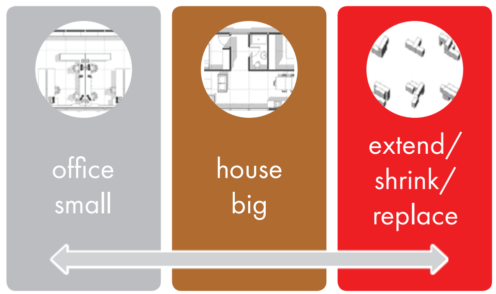
1. **Mono-functional**
transformation in mono functional context Buildings in this category have the capacity to transform the layout typology within one function as for example office building can transform layout form cell office type to open office type or to meeting room office type, without extensive reconstruction procedures and effort. Another example could be a housing block which has the capacity to transform family apartments into studio apartments or apartment for disabled without extensive reconstruction procedure.



2. **Trans functional**
transformation in trans functional context Buildings in this category have capacity to transform from one function to another, as for example office can be transformed into apartment and classroom without extensive reconstruction procedures and effort.



3. **Multidimensional Transformation**
Fully transformable buildings can be transformed form one function to another and at the same time can be extended, shrink or relocated to other location



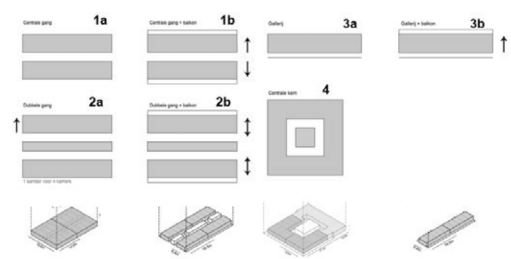
The Transformation capacity measures the effort needed to transform the buildings as well as type and number of options (as presented in previous report D12.2).

5.1.1 INDICATORS OF SPATIAL REVERISBILITY

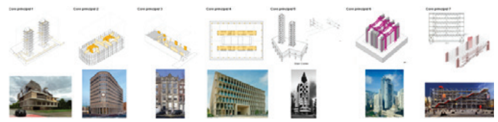
Design Parameters that have an impact on transformation capacity are: the building typology, dimensions of the buidling block, core position and distance between the cores, type of the loadbering system, method of constrution, floor to ceiling hight and window openings. Especially, the following combinations of the design parameter will impact the ability of the building to be transofmed.

The following combinations have been made to specify the rules that will determine transformation capacity (Durmisevic 2009, 2016, 2017):

1. Typology in combination with the depth and with of the block (relation to the natural light)

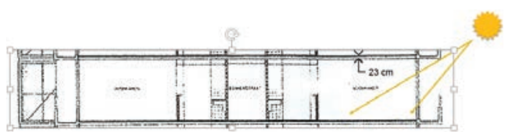


2. Typology in combination with the type and position of the core and clustering of fixed (core) elements, block dimension and distances between the cores



3. Typlogly in relation to the core, block dimension, strutural system and method of constrution

4. Floor to ceiling height in combination to the block dimension, type of the construction, floor thickens and façade opening

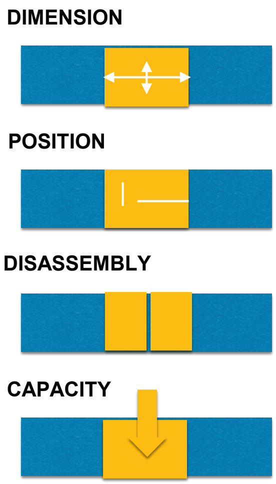


Design guidelines addressing the main design aspects of spatial reversibility are presented in table below:

The design aspects that impact spatial reversibility are specified in next chapter.

Dimensions	
building level spatial characteristics	Dimensioning of building block
	Dimension of building units
	Depth of a building block
	Dimensions between loadbearing elements (e.g. cross walls) Frame and generic space
	Floor to ceiling height
	Door openings and corridors width
	Dimensioning of the façade openings in relation to daylighting
	Dimensioning of the elevator shafts
Positioning	
Spatial characteristics	Position of circulation (central stair(s), corridor or external gallery)
	Position of loadbearing elements in relation to horizontal circulation
	Position of loadbearing elements in relation to vertical circulation
	Position of service ducts
	Position of loadbearing walls in relation to window openings
	Position of loadbearing elements in the façade
	Position of window openings in relation to the floor
Capacity	
Technical characteristics	Capacity of loadbearing structure in relation to horizontal expansion
	Capacity of loadbearing structure in relation to vertical expansion
	Capacity of the loadbearing structure in relation to internal reorganization
	Capacity of the vertical service distribution
	Capacity of vertical circulation
Disassembly Reuse potential	
Technical characteristics	Accessibility of the distribution net
	Clustering of the distribution net
	Exchangeability of variable elements
	Disassembly
	Durability

5.1.2 DESIGN ASPECTS OF SPATIAL REVERSIBILITY



Different use scenarios for a building result in different spatial typologies which again require different building structures to support transformation from one use scenario to another. The technical configuration of the building structure sets system boundaries and defines what a building structure can do to support reversibility throughout the life cycle of the building. However, this has been predetermined by the required use scenarios and associated spatial reversibility / building transformation. The balance between spatial capacity of the building and technical capacity of the structure will ultimately define the building's transformation in the future.

Four key indicators of such transformable building are (i) the dimension of space and (ii) the position of durable parts of the building structure (iii) the disassembly of main building functions/systems and (iv) capacity of the structure to accommodate multiple use options.

Once scenarios for spatial use have been determined the technical parameters that will facilitate spatial transformations and reversibility of buildings throughout its use phase need to be defined. The better these parameters are defined, the longer the building will be used. Two main technical parameters of spatial reversibility are (1) the core of the structure which needs to provide for stability of the structure and (2) facilitator of energy and climate solutions associated with spatial transformations. Together they form the technical core of a reversible building that aims at high transformation capacity of the building. When analyzing these two parameters, the main question for designers is: what is the minimum number of fixed building elements (that form the core of the reversible building) in order to provide for a maximum number of spatial transformations within a reversible building?

Therefore, initial design aspects addressed by design of transformable building can be summarized as below:

PARAMETERS OF SPATIAL REVERSIBILITY/DESIGN ASPECTS:

Transformation Model determines level of spatial reversibility. Parameters that determine Transformation Model are:

- *Volume dimensions* that are compatible with desired scenarios
- *position* of the core elements that is not restricting number of use options,
- *capacity* to carry loads and provide space for services for desired upgradability and use scenarios
- *disassembly* potential that takes care of separation of main building functions

Core design: Core is integrated base element, a minimum needed to provide for structural stability and facilitate climate, energy and comfort for different use scenarios.

Core, this most fixed part of the building needs to have capacity to facilitate transformation form one use scenario to another without demolition and waste creation

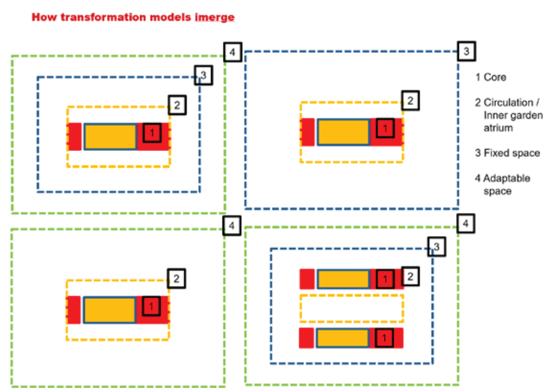


***Figure 21** specification of permanent and adaptable space through design analyses of volume building typology and position of the core elements of the building structure*

5.1.3 UNDERSTANDING HOW DESIGN INDICATORS DEFINE TRANSFORMATION

Each building with transformation capacity represents a specific transformation model including its boundaries and potentials which defined capacity of the building to accommodate different use scenarios during its use life cycles. Transformation model in general defines a ratio between more permanent spaces and elements, and variable spaces. (Figure 21) The capacity of variabele spaces to accommodate changing spatial reqirmeents depends primeraly on the horizontal and vertical dimension of the building block and the position of the main core. Different arrangement of fixed and variabel spaces and the position of the core will results into diferent building typologies. See figure below illustrating how transformation models can be shaped.

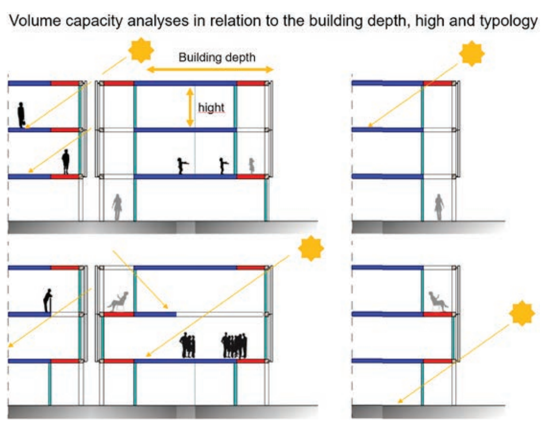


Figure 22 *Volume capacity analyses in relation to the building dept, height and typology.*

Key principles behind the high transformation capacity are related to functionality of space in relation to the block dimension (1) which provides a good quality natural light. Besides the building depth, the floor to ceiling height is a determining factor here as well. The floor to ceiling height (2) also has to provide space for installations to be added and replaced during modifications of space or function.

The floor to floor height (3) which takes into consideration the type of construction and floor thickness in relation to the flexibility of installations. The capacity of the floor to carry different loads (4). The floor capacity in housing project is for example 2KN/m2 while floor capacity for offices is 3,5KN/m2.

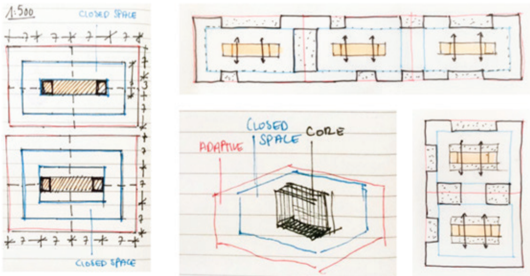
Blue colour in figure 22 represents generic part of the building while red colour represent variable part of the building and can be removed /added without affecting the main building when required. Transformation models with Red means that for example part of the horizontal roof or floor can be removed or its material can be made translucent in order to provide more light when required.

1. **Good quality natural light** is an important aspect of comfort and health (being basic qualities of building) on the one hand and energy use on the other. It therefore plays an important role when shaping transformable building volume. Glass façade with floor to ceiling height of 2,5m will reflect natural light into the space 2 times the length of the glass surfaces, which is in total 5 m. During conceptual design phase average glass service of 2,5m can be taken as a reference for creating a transformable building volume which is supported by natural light. This means that all spaces which are intensively used by people need to be within the range of 5m from the façade. Service areas, toilet spaces, book shells, wardrobes, corridors etc. can be places beyond these lines. For example, from housing point of view, if an apartment with two facades has a depth of 14m than 4m in the middle of the apartment would not have qualitative daylight (will be dark spaces). An average of 3m of service space in low light quality aria is an optimal reference that can be used during conceptual design phase. That means that for example a building block with volume depth between 10 and ca 13mm can accommodate different apartment configurations a well as school and offices since natural light could cover between 100 and 80% of the depth when transparent/ translucent separation walls are applied in office and school spaces. Thus, spatial capacity is there.

2. **Floor to floor height** is an important parameter from natural light point of view, but also from flexibility point of view, acoustics point of view and methods of construction point of view. According to Dutch regulations minimum floor to ceiling height in housing is 2,6m and average floor thickness used in new construction is 300cm which makes average floor to floor height 2,9m. In addition the floor to ceiling height of 2,8m is often used in offices and schools. If one would stick to a minimum height of floor to floor height in apartments of 2,9m than every transformation to office and classroom would be a challenge because of the intensive use of HAVC systems in offices and classrooms as ventilation ducts etc which need additional space. On the other hand, research carried out in the Netherlands for healthy schools, indicate that ceilings in schools should be higher to allow for more air and natural light. And the study of psychological comfort and people's perception of space indicate that in general human being experience higher ceilings as more pleasant spaces resulting in higher psychological comfort. The Transformation Capacity took as a departure optimal floor to ceiling height of 3m. This height complies with most of above mentioned functional, comfort and health aspects and can accommodate different transformation and configuration options of housing, offices and schools from bought physical and psychological comfort point of view.

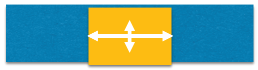
3. **Floor to floor height.** In addition to floor to ceiling height a dimension of floor slab is added as well as the space for installations. When changing function of space, number of installations need to be modified. This means that distribution network of installations need to be accessible and therefore separated from the floor or integrated in the floor structure in a way that modifications will not cause damages to the floor. Taking this into account TC takes into calculation two major types of construction (1) solid structure with solid floors and (2) post and beam structure which allows for integration of installations in decided accessible zones between the beams. If solid floor is applied than additional space is added on top of the floor thickness to allow for easy distribution of installations. That means that for example floor to ceiling height required would be calculated as 3m (floor to ceiling height) + 0,3m (floor slab) + 0,6m (installation space for office function).

Transformation model
(Sarajevo workshop results)



5.1.4 DESIGN PRINCIPALS BEHIND EACH INDICATOR

DIMENSION



Dimension Design of Building with high Transformation Capacity starts with understanding spatial capacities of different building typologies. For example, a building block 25m deep associated with typology 1 (see below) cannot become a comfortable and healthy housing block because 65 percent of its service does not have natural light. If designer is designing a new building than when building depth becomes bigger, she/he can consider adopting other typology for example typology 2 (see figure 23 below) with air and light pockets or moving to typology 4. (this type of direct feedback as a part of design support is provided through virtual simulator presented in D12.3)

Building block in the figure below is optimized to support multiple building functions taking into account

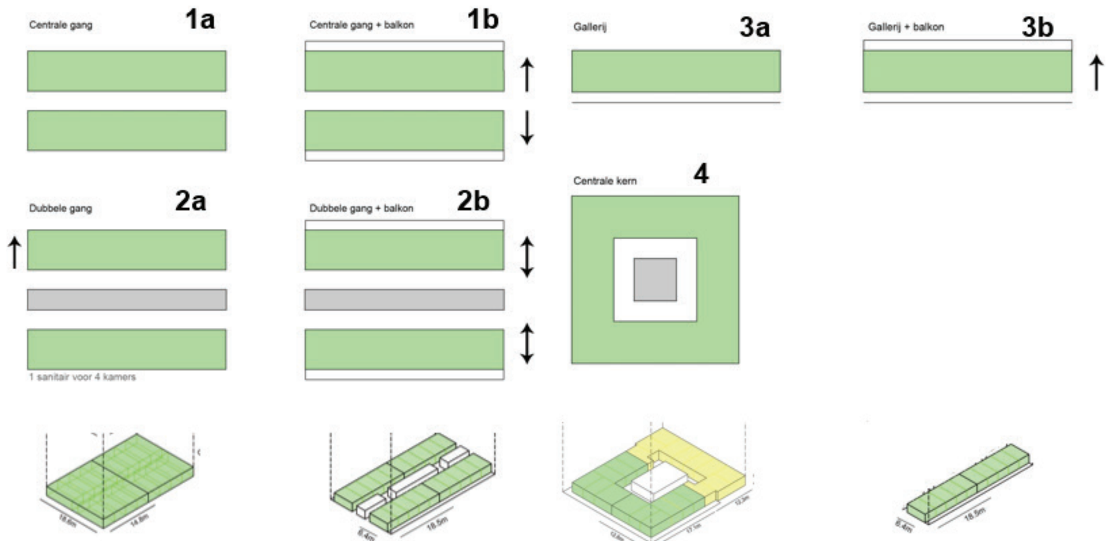


Figure 23 *Four main building typologies*

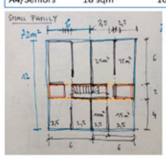
above mention principles illustrates typology 2 (double corridor) type of building block which can accommodate housing and office functions.

Schemes below zoom into the building units forming the building block in order to understand their transformation potential and optimize structural grid.
To summaries when designing a transformable building the Block Dimension provides an information on spatial capacity and compatibility of spatial organizations and functions.

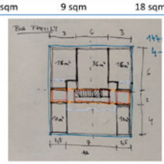
Figure 24 *Multiple functions and layout option within one building block*

A / HOUSING

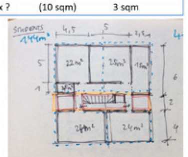
Type	Living Room	Kitchen	Bathroom	Bedrooms	Workspace	Storage
A1/Small family	14 sqm	7 sqm	5 sqm	14 sqm x ?	8 sqm	3 sqm
A2/Big family	> 16 sqm	> 7 sqm	> 5 sqm	14 sqm x ?	8 sqm	> 3 sqm
A3/Students	(10 sqm)	3,5 sqm	3 sqm	> 10 sqm x ?	(2 sqm)	2 sqm
A4/Seniors	18 sqm	10 sqm	9 sqm	18 sqm x ?	(10 sqm)	3 sqm



Option 1



Option 2

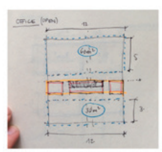


Option 3

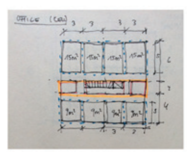
B / OFFICES

Type	1 pers	10 ppl	Cell	Open office	Google
B1/Leadership	10 sqm	100 sqm	10 sqm	8 sqm	5 sqm
B2/Fixed	5 sqm	50 sqm	5 sqm	4 sqm	5 sqm
B3/Flexible	3 sqm	30 sqm	-	3 sqm	5 sqm
B4/Free Address	1,5 sqm	15 sqm	-	2 sqm	5 sqm

Workplace 2.0 fit-up standard (Canada)



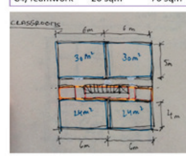
Option 4



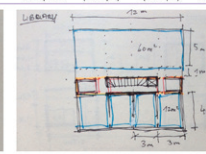
Option 5

C / EDUCATION

Type	Classroom	Lecture	Offices	Hall	Lockers	Technics	Kantin
C1/Elementary	35 sqm	- GYM ?	40 sqm	30 sqm	20 sqm	10 sqm	30 sqm
C2/Uni. Campus	30 sqm	70 sqm	10 sqm x ?	> 30 sqm	> 20 sqm	15 sqm	> 30 sqm
C3/Library	15 -20 sqm	70 sqm	10 sqm x ?	30 sqm	> 30 sqm	20 sqm	20 sqm
C4/Teamwork	20 sqm	70 sqm	10 sqm x ?	(20 sqm)	(15 sqm)	15 sqm	15 sqm



Option 6



Option 7

Scheme A Building block 12x12m with central corridor designed as housing for two small families (option 1); Big family (option 2) and four studios (option 3)

Scheme B Building block 12x12m with central corridor designed as office open office space (option 4) and cell office type (option 5)

Scheme C Building block 12x12m with central corridor designed as three workshop/ small classrooms (option 6) and big classroom/ possibly library (option 7) (International design Studio 2016

POSITION

The next design aspect that indicates the capacity of the building is the **position** of the core of the building. As illustrated in the schemes above, if the cross-wall building method would be applied on the construction span of 3m than only option 1 and option 5 would be feasible out of 7 use options that block dimension provides. The number of options would be different if post and beam system would be implemented.
Besides the type of structure, another important parameter which is analyzing the position of more durable parts of the structure is the type and position of the core. In order to design buildings with high Transformation Capacity clustering of the core elements (loadbearing, installation, communication) is an important design aspect as well as their position which should be a more peripheral position. The figure below illustrates distinct types of cores and their positions. The clustering of the core elements will minimize the number of more fixed parts of the building which can form a barrier during transformation, while peripheral positioning of the core elements would provide more use options to the adaptable space.
Examples of these principles are presented in schemes below.

Peripheral position of the horizontal installation net enables different office typologies. Central position of horizontal net in office building forms often a barrier in the middle of the building due to the reduced corridor height. Peripheral position as illustrated in figure 31 allow development of office cell type and open office type.

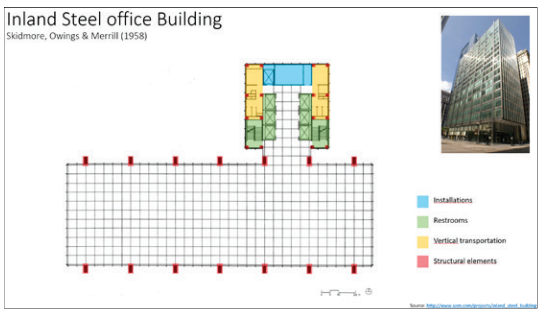


Figure 25 *Peripheral clustered loadbearing, communication, installation core*

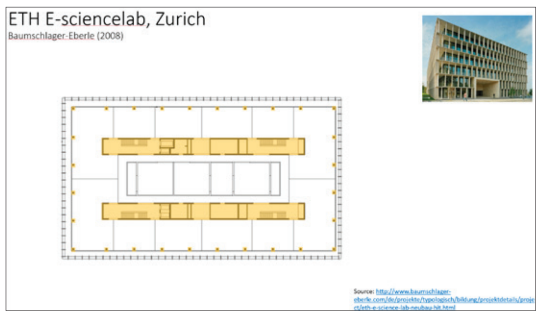


Figure 26 *Off-center clustered loadbearing, communication, installation core*

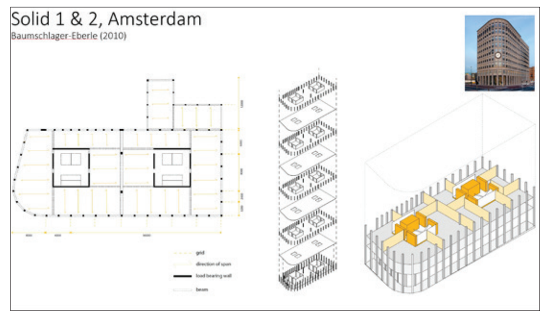


Figure 27 *Central clustered loadbearing, communication, installation core*

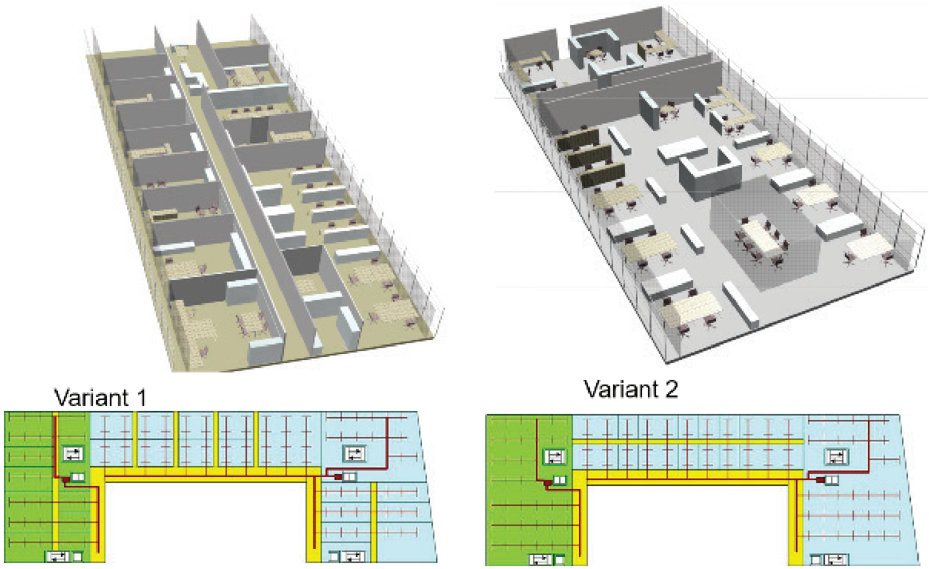


Figure 31 *peripheral position of horizontal distribution of technical services enables different office typologies, 4D architects, Amsterdam 2003)*

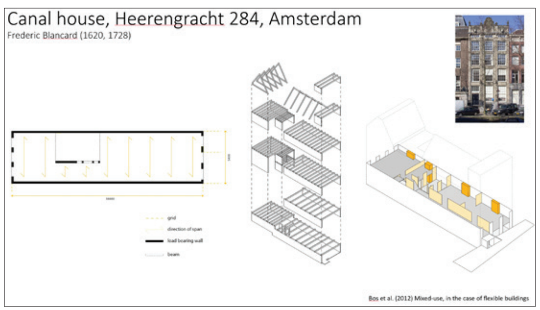


Figure 28 *Peripheral clustered loadbearing, communication, installation core (Bos et al 2012)*

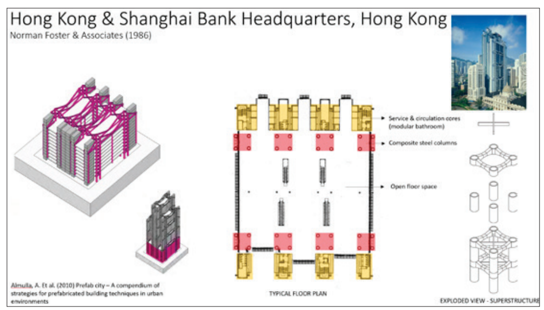


Figure 29 *Peripheral clustered loadbearing, communication, installation core*

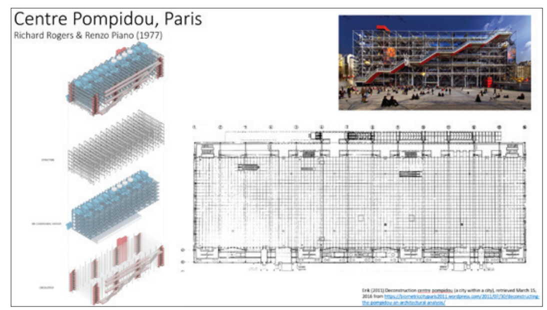


Figure 30 *Peripheral clustered loadbearing, communication, installation core*

DISASSEMBLY

Disassembly This indicator analyses the functional decomposition on the building level and whether it is possible to disassemble façade, floor, roof or partitioning walls and services during the transformation process without affecting other functional parts of the building. The principles applied here are the same principles addressing functional independence as indicator of technical reversibility in chapter 3.

Besides the independence of functions, the accessibility to the installation distribution network is an important indicator of transformation without demolition as well as the space available for additional installation services. Major Building functions on the building level are: the support structure, the horizontal partitioning (et. Floor/ roof slabs), the vertical partitioning (partitioning walls between different spaces of the building), the vertical enclosure (et façade), the horizontal enclosure (et roof), vertical services (et main service net), horizontal services (horizontal service net)

Figure 32 *Disassembly options of main building function on building level*

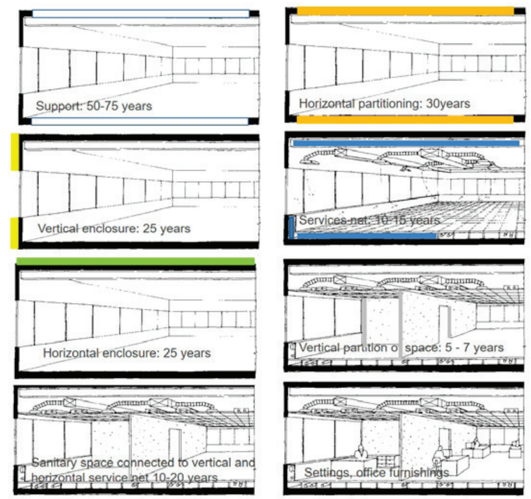


Figure 33 *overview of main building functions*

While defining the level of functional decomposition on the building level during the conceptual design phase the future potential of the building to transform the performance and position of main building functions will be defined. This is also true for the transformation of the existing building.
An existing building which has the dimensional and structural capacity to accommodate different requirements can be transformed by integrating new dismountable functional layers which will allow future transformations as well. Figure 34 illustrats variable functional layers attached to the existing housing block (permanent layer) in Enschede,(4D architects, Amsterdam 2009)

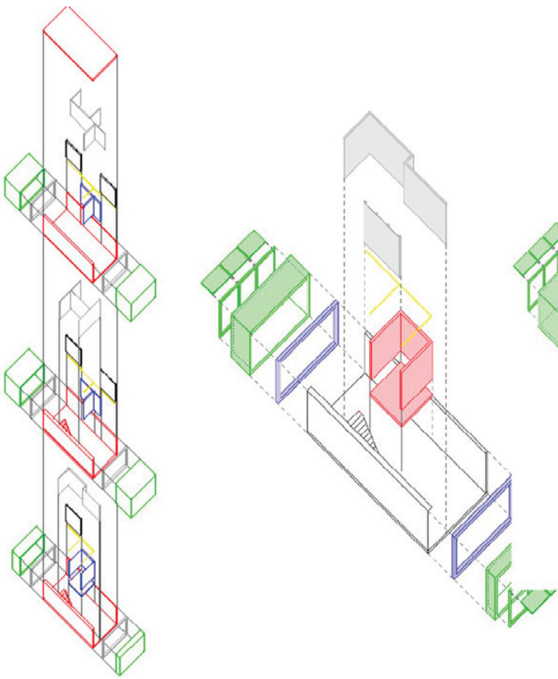


__Figure 34__ Functional decomposition on building level: Wight surface represent existing permanent building structure; Red representing more permanent part (support, main technical services) of the structure but yet designed with the capacity to be disassembled at the end of the use life, green representing variable / exchangeable parts of the structure and blue representing intermediary between the permanent and variable parts of the structure while gray represent replaceable infill elements.

CAPACITY

Wether the floor has enough **capacity** to support the different functions is crucial when analyzing transformation capacity. If that is not possible than all other factors cannot help to enable functional transformation of the building.
It is important to take into consideration that the floor capacity in housing projects is 2KN/m2, offices 3,5kN/m2 and public building 5KN/m2. Another important design aspect is the availability of space for the placement of new installations. This is taken care of when defining floor to floor height and type of construction as well as by dimensioning of the vertical service core. Transformable Building Design is not in favor of providing overcapacity of the installation services for the potential future use in the initial construction phase. It is in favor of future additions when required, by modular plugins. This means that possible future modular additions of installations should be possible.

5.2 TECHNICAL REVERSIBILITY

Reversible buildings recognize three levels of technical composition/decomposition is:

- Building level represents the arrangement of systems, which are car¬riers of the main building functions (load bearing construction, enclosure, partitioning, and servicing),
- System level represents the arrangement of components, which are carriers of the system functions (bearing, finishing, servicing) - the sub-functions of the building.
- Component level represents the arrangement of elements and materi¬als, which are carriers of component functions, (such as bearing, finishing, servicing component) (Durmisevic, 2006).

5.2.1 DESIGN DOMAINS OF TECHNICAL REVERSIBILITY

Reversibility of building structure is defined by three design domains; namely functional, technical and physical design domains:

- Functional domain: deals with functional decomposition and allocation of functions into separate materi¬als, which have different changing rates. This domain defines functional dependences
- Technical decomposition deals with hierarchical ar¬rangement of the building materials, and relations as well as with hierarchical dependences between material levels.
- Physical domain deals with interfaces that define physical integrity and dependences of the structure.

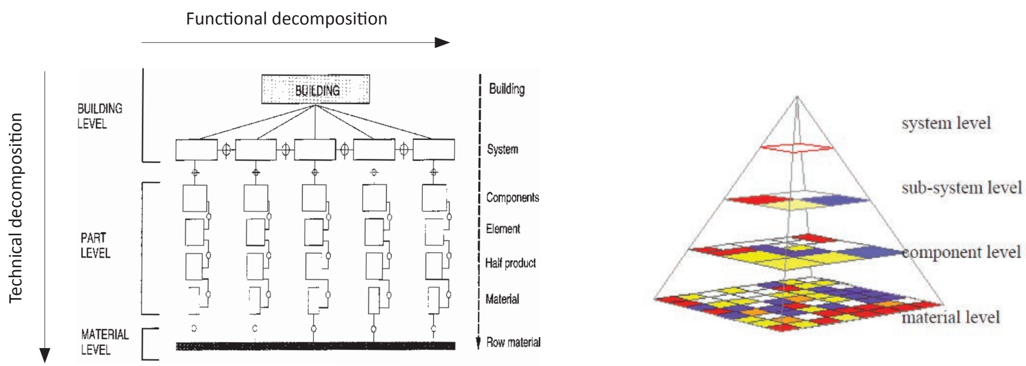


Figure 35 *Hierarchy of levels of technical decomposition of reversible buildings (Durmisevic, 2006)*

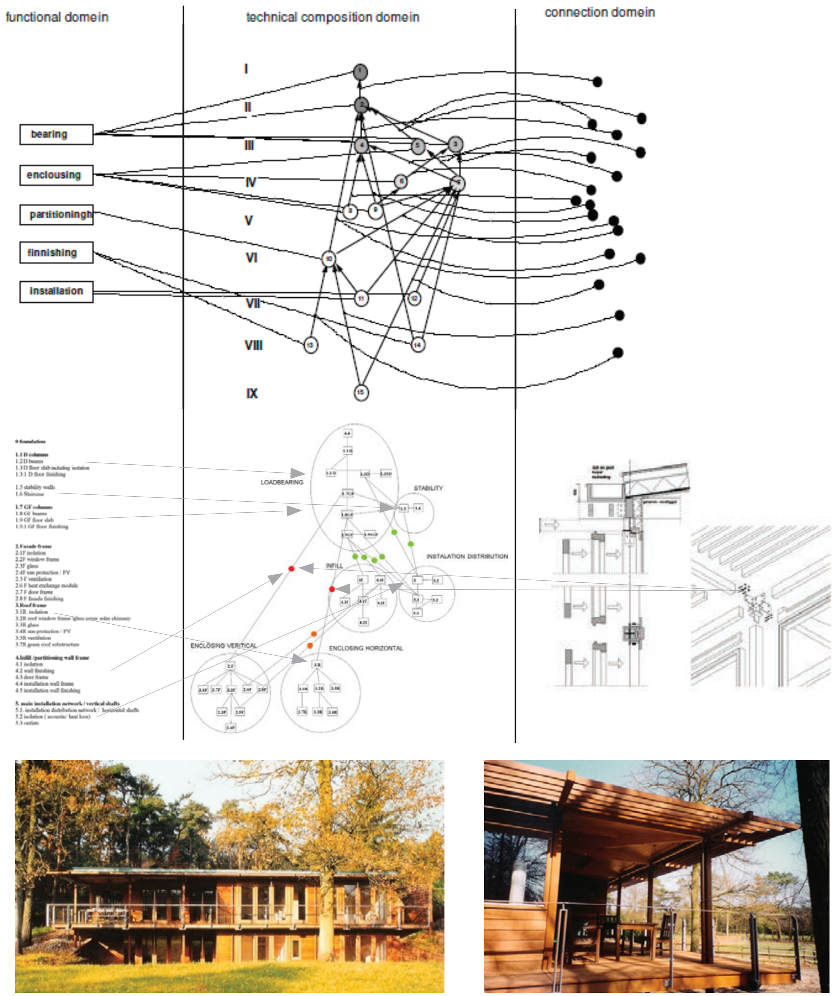


***Figure 36** overview three key design considerations provisions of functional independence left by arrangement of building parts and group of part performing same function into an open hierarchy of parts and design of base elements and reversible connections which will guaranty physical independence of building parts (Design for Disassembly, Durmisevic 1999, 2016)*

Reversible configuration is regarded as the process of creating an arrangement from a given set of elements by defining the relationships between the selected elements and their functions in order to perform a desired function, and in a way that will satisfy requirements and constrains for disassembly, reuse and reconfiguration/ transformation.
Functional decomposition provides independence of functions through allocation of building or system functions into independent modules, which respond differently to changing needs and have different changing rates. During reversible configuration design, a designer allocates functions to a sets of elements and determines their relations (Figure 36). As a design activity, configuration design can be seen as an activity concerned with different relationships and interdependencies. Defined set of relations and ele¬ments result in the physical state of the structure, which informs us how performance requirements are translated into materials, and how materials are integrated into a system or a building. Ultimately this will determine the (sub)system reversibility (Durmisevic 2006).

If for more functions are represented by one physical level, for example a wall which integrates five functions (1)support, (2)finishing, (3)insulating, (4)carrying installation services and (5)door openings, (see diagram left in the figure 37) there is a risk that due to the change of one of the functions the part of the wall or the whole wall needs to be demolished. Functional /technical decomposition of such a wall is illustrated in figure 37 left. One wall solution optimized to enhance modifications without demolition and waste creation is presented through functional /technical decomposition diagram in figure 37 right, illustrating functional independence of different wall functions by predominantly more vertical relations between elements and only two functional dependencies between electric wiring and the door frame e)

Design aspects that have influence on decision-making dur¬ing design of reversible building product structures are:

1. **Functional independence:** rating the level of separation of functions that have different changing rates and use expectances
2. **Systematisation:** clustering of elements into an independent module based on functionality, assembly/disassembly, life cycle coordination of elements and their expected use life cycle assembly
3. **Relational dependency and relational pattern:** minimization of the number of relations representing functional and technical dependences between elements within a building
4. **Base element of the configuration:** design of base element that functions as intermediary between the elements within the configuration.
5. **Assembly/disassembly sequences**: allowing for more parallel then sequential assembly within a building
6. **Geometry and morphology:** design the geometry of product edge that will allow for recovery of elements without damaging themselves or elements, and geometry of product edge that is suitable for reuse.
7. **Type of connections**: use type of connection that will allow for separation and easy recovery of elements. Unlike conventional structures in which design deals with functional, techni¬cal, and physical composition, the design of reversible structures considers functional, technical, and physical decomposition.
8. **Life Cycle Coordination of elements**: coordination of use and technical life cycle of elements within buildings in relation to their disassembly sequences

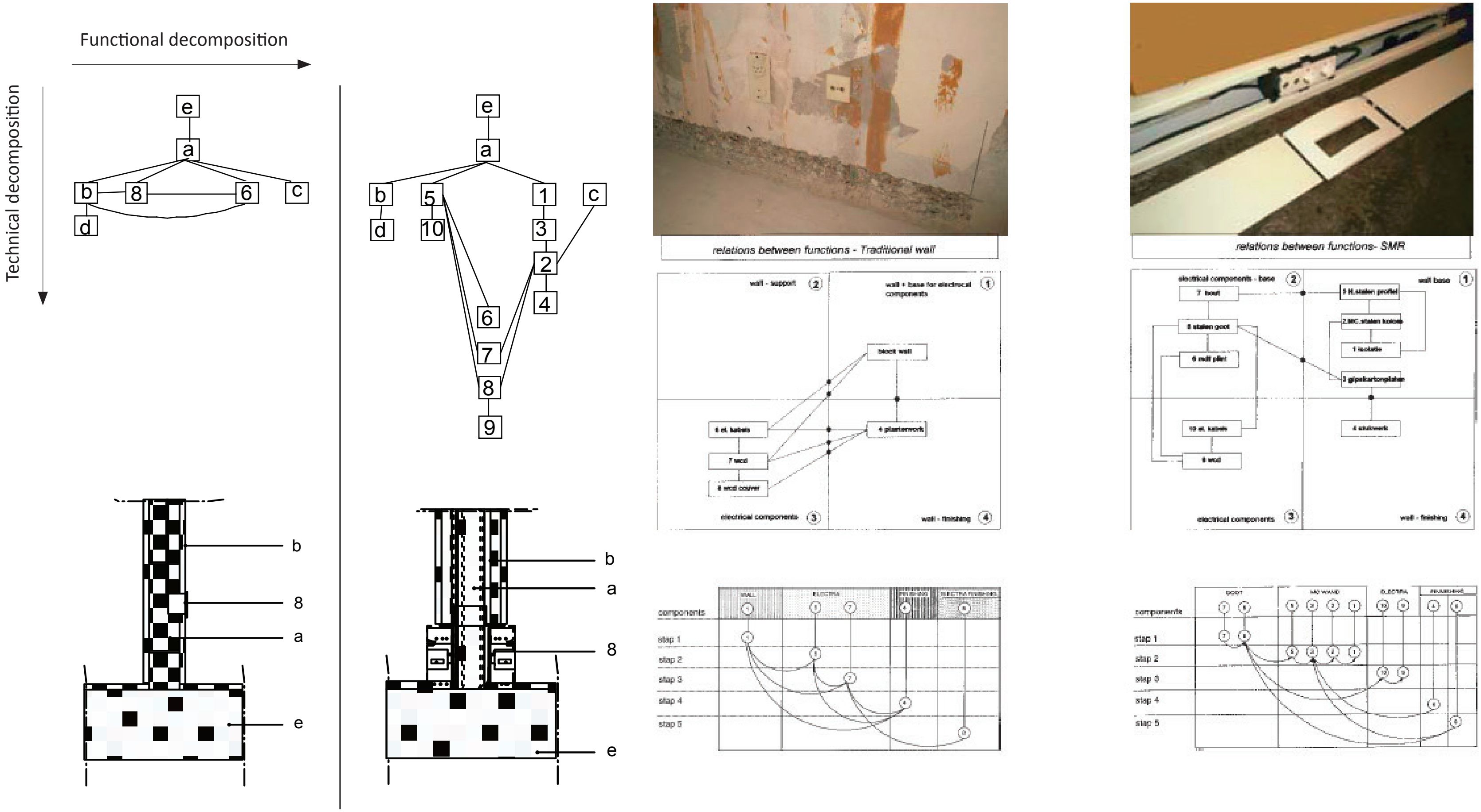
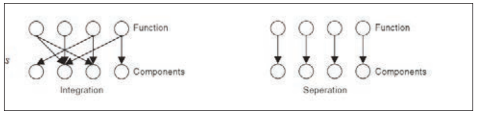


Figure 37 *left diagram showing functional/technical dependence of elements within conventional wall, base of the wall (a), electricity outlet (8), data and electricity cables (6), finishing of the wall (b), door(c) and their full integration and dependency represented by number of horizontal relations between main functions. Diagram right functional/technical independence within flexible wall represented by more vertical relations between different functions.* ***Far right:*** *alternative view on functional dependences. Four squares represent for functions of the wall (1) bearing, (2)servicing (distributing services) (3)finishing, (4) insulating. Relations passing the line of functional squares represent dependences.*

1. FUNCTIONAL DECOMPOSITION



Functional Separation

A building component can be taken from a building, if it is defined as an inde¬pendent part of the building's structure. The first step that must be made is to subdivide the building into different sections that have different performances and different life cycles.

Four main building functions are: supporting, enclosing, servicing, and parti¬tioning. Each of these can further be subdivided into subsections (subsystems) such as: foundation, frame, floor, façade, roof, inner walls,

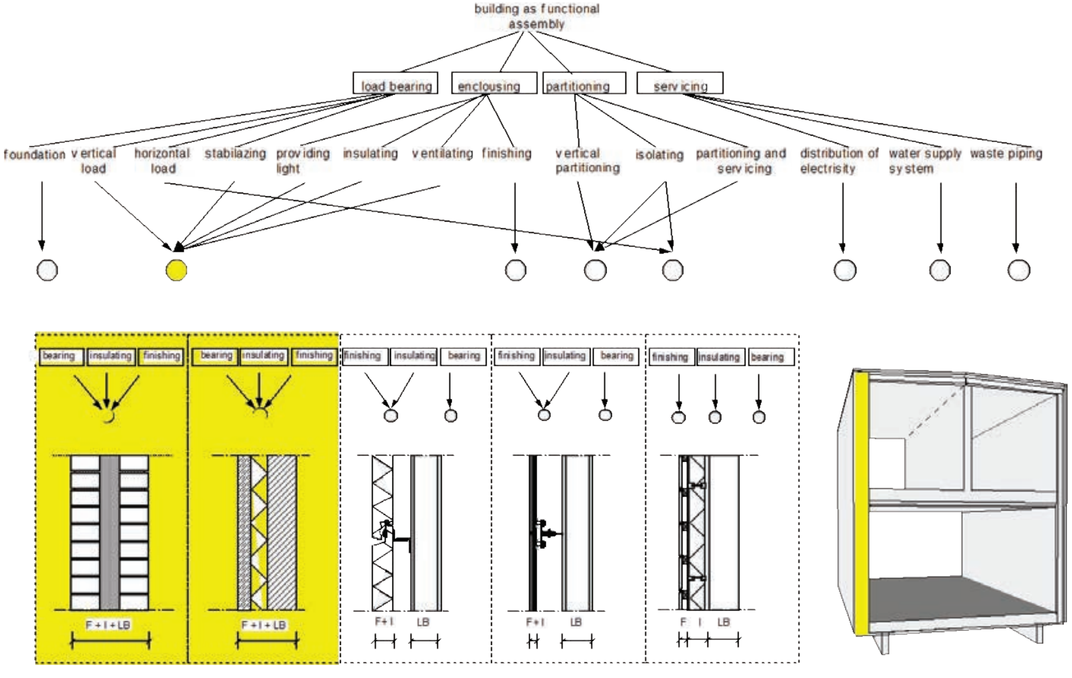


Figure 38 *options representing functional independence/ dependency of the building exterior wall.*

ventilation, heating system, water system, electrical system, etc.
Each of these functions has different behaviors, and provides different ef¬fects such as: heating, reflecting, distributing, ventilating, lighting, or deals with effects such as tension, compression, etc. Therefore, the integration of two or more functions into one component can freeze transformations that may be needed to address new user requirements. Different functions may have different life cycles.

Just as a building, the building system, such as a façade system, has also generic functions that form the system comprising the support/base, the enclosure, the finishing and the servicing. If individual elements/ products represent individual functions than a system will be reversible. (see example of a reversible bathroom system in Figure 39. Main functions of the bathroom (wall support , technical services, finishing and bathroom accessories) have been defined as independent functional elements and are connected only with intermediary steel elements (see figure 39). Steel elements form at the same time interface between the main permanent building structure and variable elements of the bathroom system. Such technical decomposition enables replacement of finishing without affecting installation or support of the system as well as moving a accessories as sink from position A to position B without effecting other elements of the system.

The same approach of functional decomposition can be applied to the product level as well so that product is reversible and can change its functions as illustrated in the figure below. Bathroom wall module with frame, technical services, finishing and sink can be reconfigured into a shower module by removing the finishing panel which is independent of other element and by accessing technical service via dedicated installation zone.

Figure 39 *flexible building system defined by full separation of the main system functions (4D architects, Amsterdam 2009)*

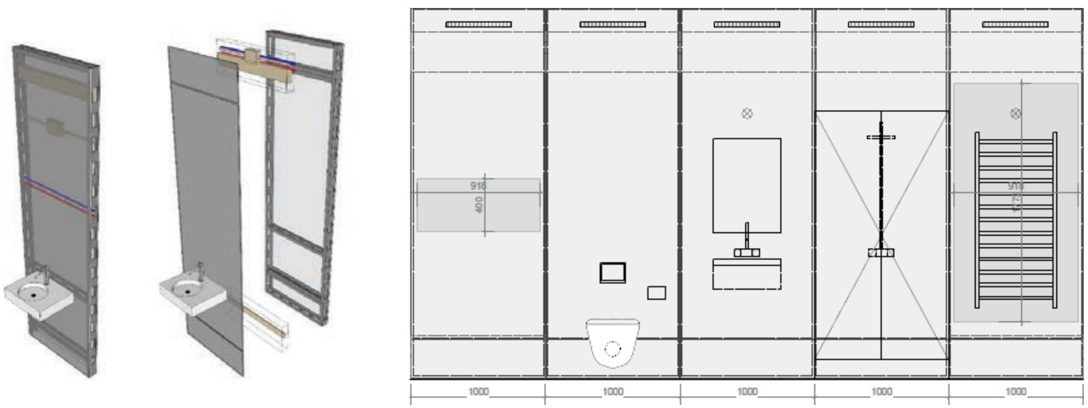
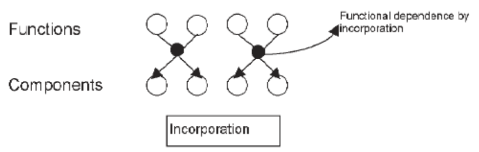


Figure 40 *Flexible product made of elements representing individual functions. (4D architects, Amsterdam 2009)*



Functional autonomy Incorporation provides a partial dependency between independent func-tions by planned or unplanned interpenetration of components having different functions.
This means that relocation or resizing of components that have one function influences the integrity of other components that have other functions.
Five types of integration are defined based on Durmisevic (2006), as shown in figure 41: 1) No dependency, is used when there is no dependency between the installation and the sub-function, 2) Modular zoning, a dedicated area is used to cluster different types of installations, which allows for easy access or modification, 3) Planned integration, a specific area is dedicated to the installations and allows for small modifications or additions, 4) installations are integrated with other building functions with no excess space for future modifications or additions, and 5) the installation is entirely integrated in other building functions and does not enable access without destructive operations.

The incorporation of independent functions, result in the following strategies:

Strategy 1:
total separation or zoning (modular zoning)

Strategy 2:
planned interpenetration of installations and load-bearing elements, such as: pre-made holes, and voids made especially for services.

Strategy 3:
unplanned interpenetration of installations and load-bearing element by provision of a free zone.

Strategy 4:
total integration. Structural elements can act as parts of a building's service system. For example, thermal inertia of a structural element may be exploited to store heat; the structure may absorb or reflect sound; parts of the structure may be filled with water to provide active fire protection, etc.

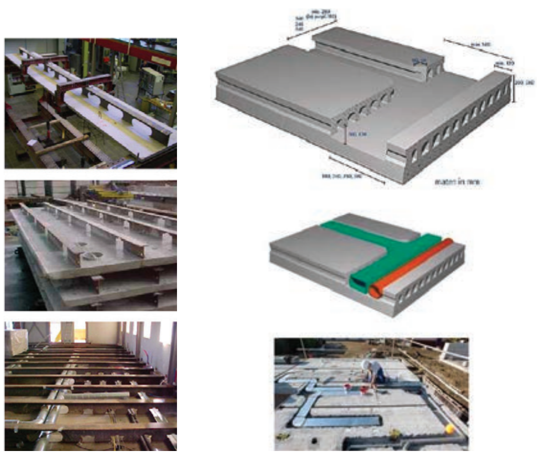


Figure 42 *Examples of functional incorporation*

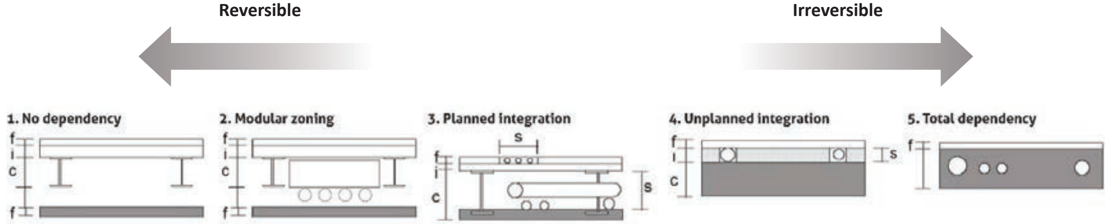
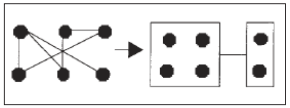


Figure 41 *Schematic representation of five types of integration, the letters in the figure represent the following functions: (c) structure, (f) finish, (s) servicing and (i) insulation. (Durmisevic 2006)*

2. SYSTEMATISATION



The number of disassembly options can be an obstacle for reversibility. If too many disassembly sequences are required, one may choose demolition instead of disassembly. This brings into focus two-stage assembly and disassembly. First, at the building site, where higher-level sub-assemblies like systems and components are disassembled at the building site, for reuse/reconfigu¬ration. Secondly disassembly in factory, where lower levels subassemblies, such as sub-components and elements, are disassembled and repaired for reuse/reconfiguration/recycling. If a building is composed of elements and components the

number of disassembly steps that are required to demount the building will be much greater than a building composed of elements, components, assemblies & units, as shown in Figure 43. According to the different building levels the number of material levels will be assessed based on the identified product levels, which are provided in input level 2 of the reuse potential tool at level of prefabrication and will be assessed according to the assessment criteria shown below.

If many steps need to be performed at the construction site in order to recover building parts the deconstruction process is often financially unfeasible.

The aim of reversible building design is a bigger level of assembly as possible (component/module/system level). This is as a mean to reduce assembly/disassembly time at the construction site and encourage disassembly in factory which is the most effective way of resource productivity.

For example, the preassembled extension module of GTB lab can be disassembled back to the initial elements without damaging them. (Figure 45)

When analyzing the relational diagram of the initial design solution of GTB Lab moduele, it was evident that elements within the structure had great number of relations resulting in a great number of disassembly steps

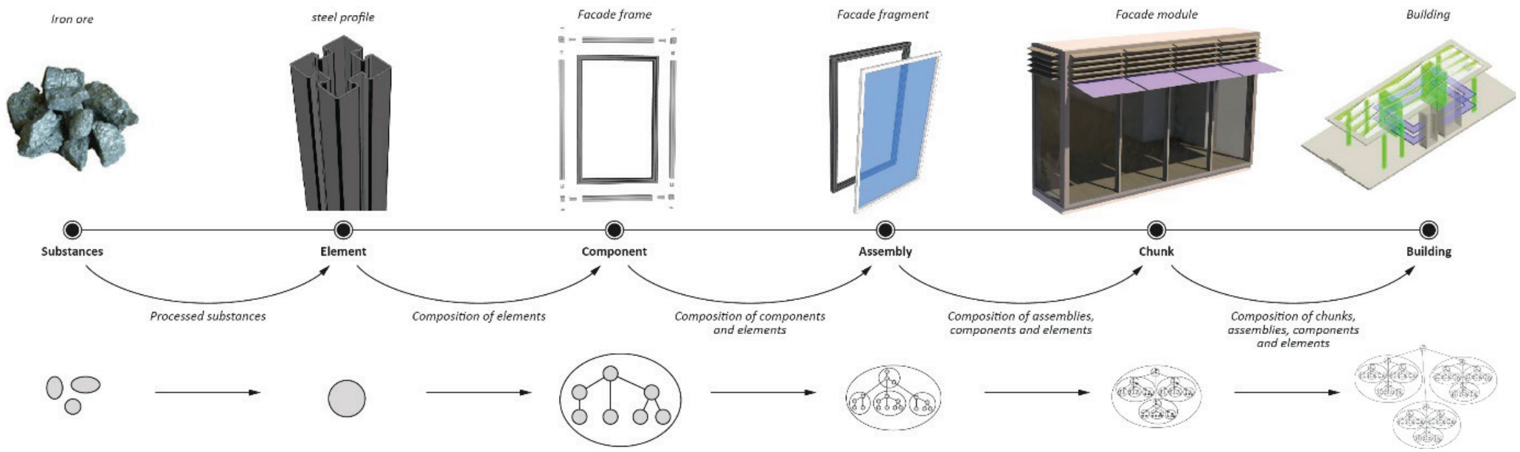


Figure 43 Levels of assembly, aiming at assembly on bigger level of technical composition of the building

as well as dependences in assembly and disassembly. The points of improvement here were primarily related to the systematization / clustering of elements on subsystem level of a unit as roof, floor and ceiling into preassembled subassemblies that can be assembled and disassembled into a steel frame of the module quickly without affecting others. In order to achieve this the base element within each cluster has been introduced as well as the intermediary between the base element and the cluster (see indicator 4: Base element). This has resulted into an arrangement of building parts which are clustered into independent subassemblies according to their functionality and can be independently disassembled and replaced. This also results in faster assembly since the number of assembly steps on the construction site have been drastically reduced.

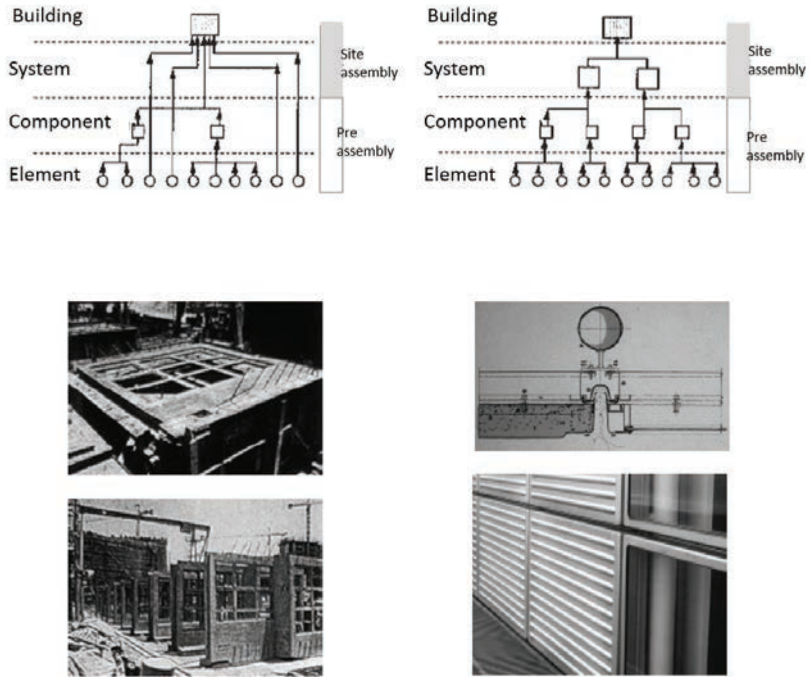


Figure 44 *Building product levels*

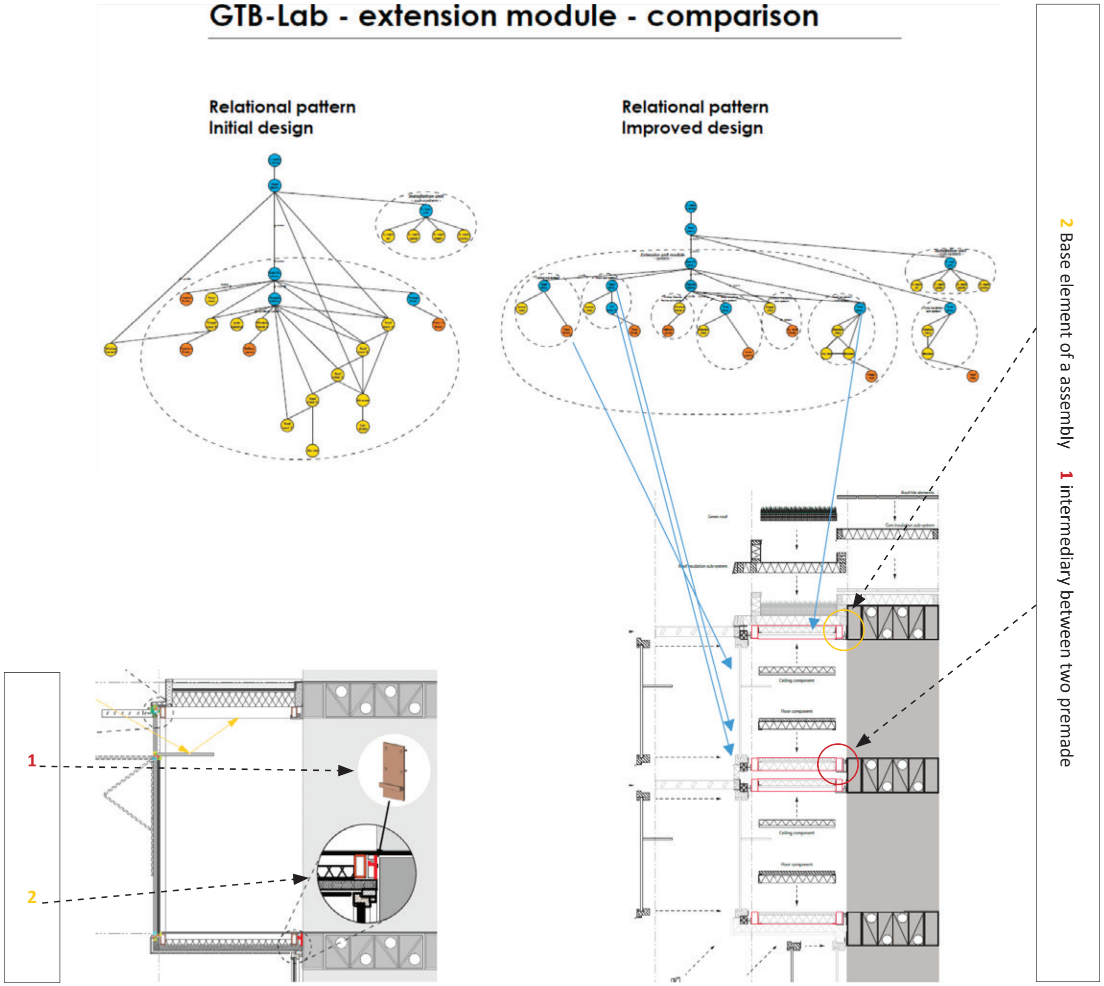
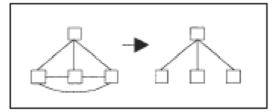


Figure 45 Left the initial design of replaceable GTB Lab module involves assembly of all parts of the module on element level on the site. Right the improved design allows independent modifications disassembly of complete roof, floor and façade.

3 RELATIONAL PATERN



Two aspects are addressing the relational pattern: Pattern type and position of relations

Pattern type

Traditional buildings were characterized by complex relational diagrams, which represented maximal integration of all building elements into one dependent structure.

In such an environment, substitution of one element could have considerable consequences on related parts at their connections.

The most important aspect that influences the disassembly potential of struc¬tures, is the number of relations. Distinction can be made between five relational patterns that result in five types of assemblies (Figure 46).

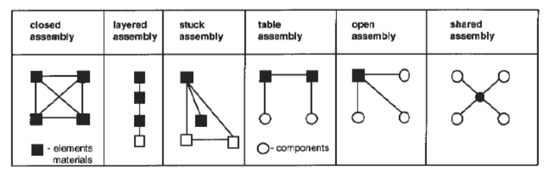


Figure 46 Patterns representing five types of relations between building elements 1.closed assembly , 2.layered assembly, 3.stuck assembly, 4.table assem¬bly 5.open assembly

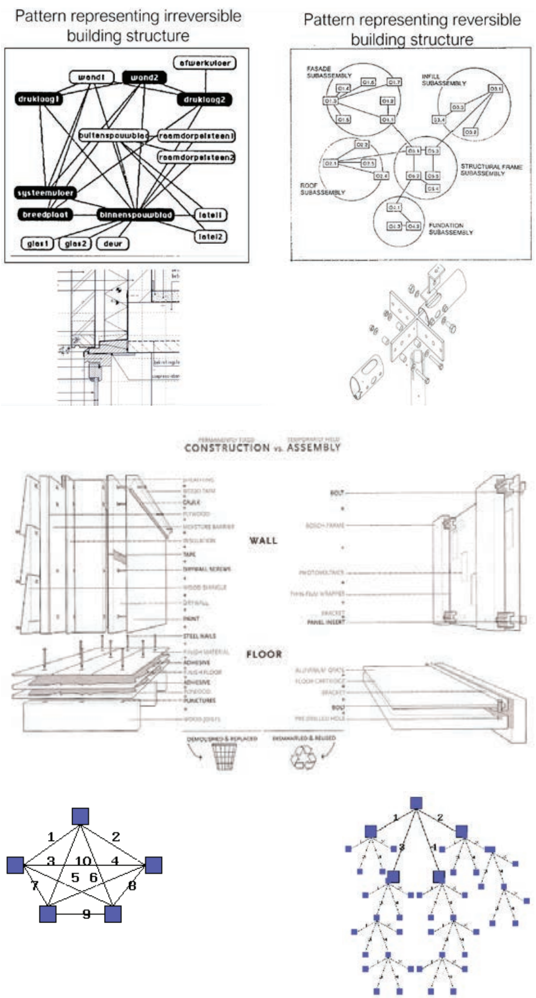


Figure 47 *examples of patterns of relations between building elements which represent irreversible building structures and reversible building structures Fixed configurations represent patterns that result in closed, layered, or stuck assemblies. The table assembly characterizes partially open systems. While open hierarchy are represented by building parts that are kept independent from one another by creating dependent relations only with one element within an assembly (base element of configuration).*

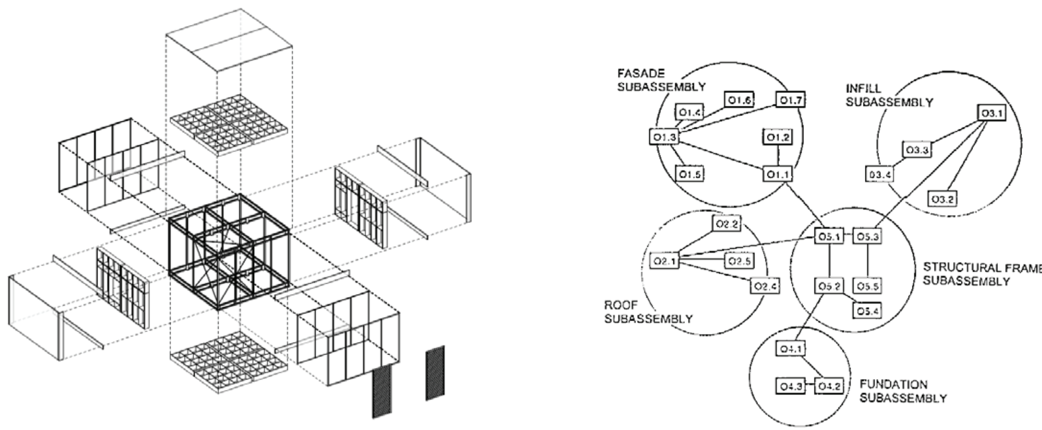


Figure 48 *relational diagram and scheme of GTB Lab module, and assembly of reversible floor, roof and façade cluster of GTB Lab module*

Figure 49 *Assembly of the steel frame which functions as a base for other clusters as façade, roof floor. All are independently produced and assembled independently from each other (GTB Lab)*

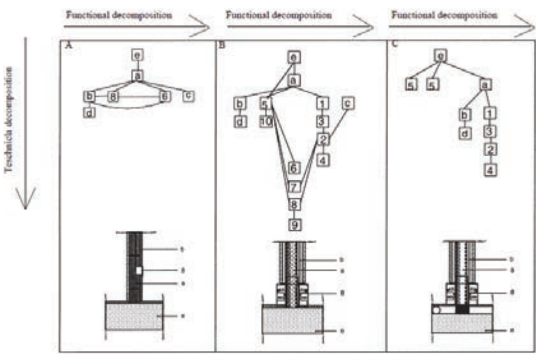


Figure 50 *Vertical relations represent relations within one functional group, while horizontal relations represent relations between different functional groups.*

Position of relations

Relations within sub-assembly versus relations between sub-assemblies

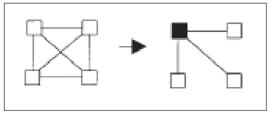
The relational diagram (see below) can be interpreted as representation of functional and technical decomposition. Functional decomposition is presented as horizontal row of elements representing individual function, while each function in a row can have its column representing technical decomposition within one family group.(see figure below). The aim is to avoid relations between different functional groups which are represented by a horizontal/diagonal lines.

The main rule is that sub-systems representing independent functions should only have relation via one support of the base element of the structure (see indicator 4 base element).

Ideally, different functional groups should not be directly related. Diagram left represent functional and technical decomposition of a conventional partitioning wall having five functions (b)support _building blocks, (d)finishing, (6) insulating, (8) installation services and (c)door openings. All five functions are mutually interrelated which results into more horizontal relations connecting all functions. Diagram in the middle represent one type of flexible wall solution.

Most of the functions are materializes as independent clusters and have relation with the base of the system. Only finishing (8) has relations with two functional clusters which are created in the low levels of technical decomposition creating more horizontal/diagonal relations between two functions. This means that there is a functional dependence which may involve number of deconstruction stapes while affecting and potentially damaging two functional clusters.

4.BASE ELEMENT



A building product (system/component/element) is a carrier of specific building's functions. Each assembled product represents a cluster of elements that are carriers of sub-functions. To provide independence of elements within two clusters, each cluster should define its base element, which integrates all surrounding elements of that cluster. This element functions as intermediary between elements as well as between clusters. Such intermediary share functions on two levels: (i) it is connecting elements within the cluster and (ii) perform as an intermediary with other clusters. Base elements/ intermediaries can be found on all levels of technical composition of a building (figure 51).

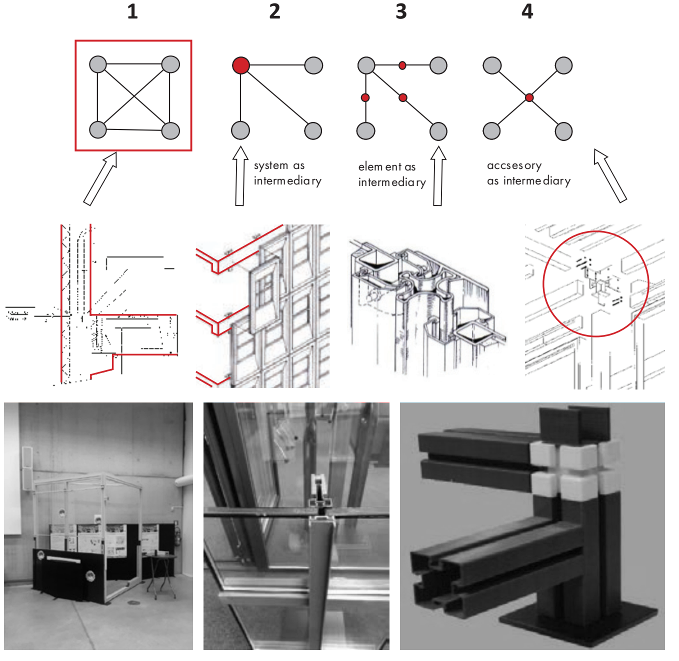


Figure 51 *The whole building with its exterior walls, interior walls is a base* **(1)** *loadbearing structure as a base element (building level)* **(2)** *a frame within a system as a base (system level)* **(3)** *intermediary connection which connects multiple elements as a base (element level)* **(4)**

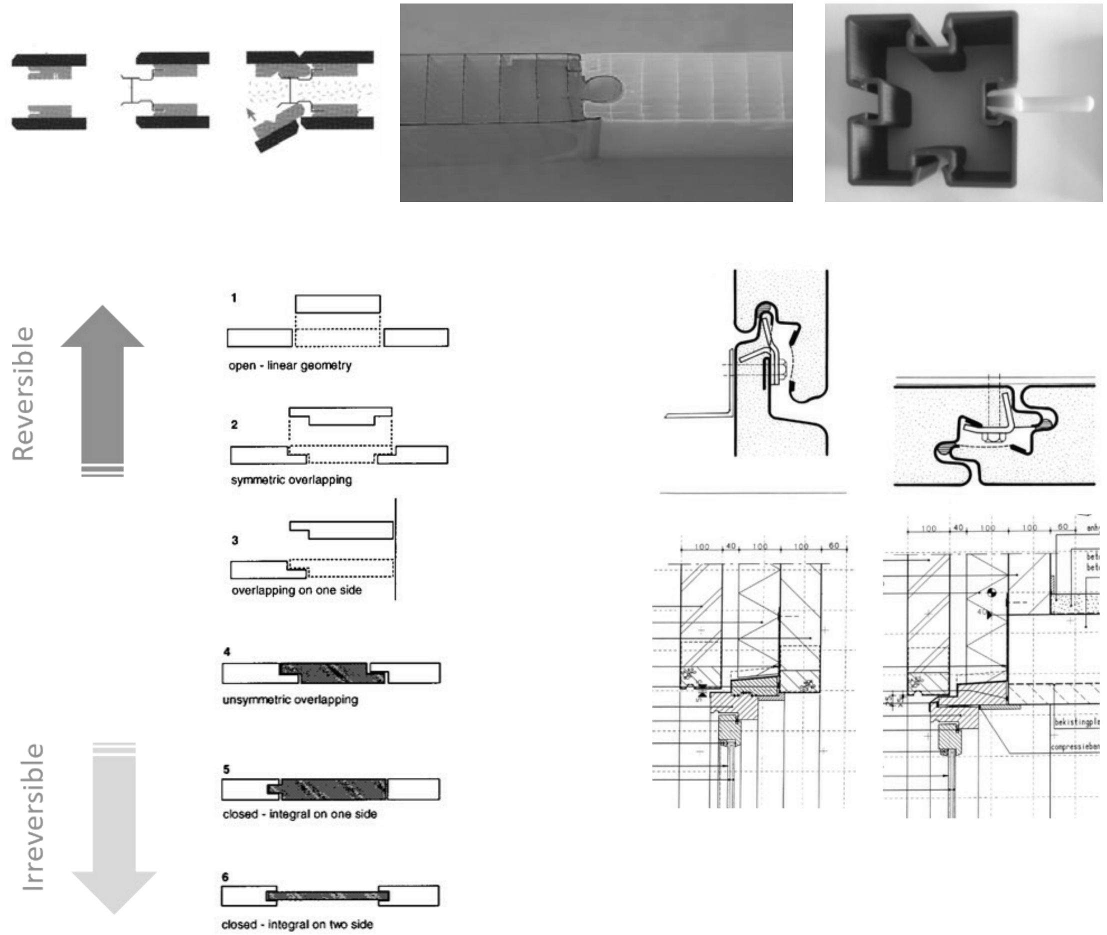
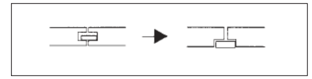
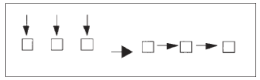


__Figure 52__ overview of principles geometries of product edge

5. GEOMETRY OF PRODUCT EDGE



Reversibility / Disassembly can be affected by changing of the geometry of product edge. This is closely related to the interface design and specification of the connection type. It is possible to identify six situations that define the suitability of the geometry for disassembly of components. Two major distinctions can be made between open and interpenetrating geometry. The interpenetrating geometry is less suitable for disassembly, since elements can be disassembled in only one direction. In the worst case, components can be removed only by demolition of connected elements.



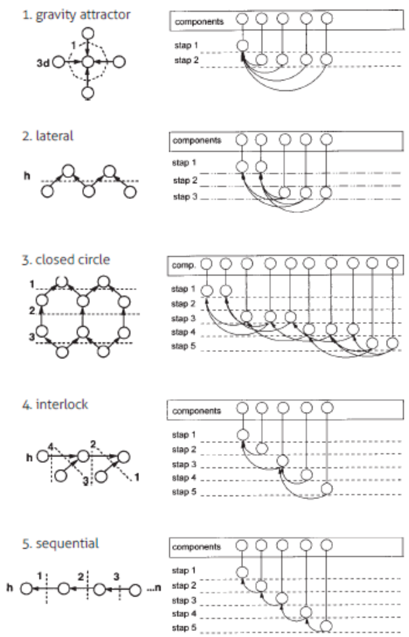
6. ASSEMBLY SEQUENCES

Life cycle of assembled materials, type of materials, geometry of product edge, and type of connections influence assembly/disassembly sequences.

Sequences in assembly represent the complexity of the structure and dependen¬cies between building elements. The way we assemble a building sets the mirror image of the building during its transfor¬mational and disassembly phase. Two mayor assembly/disassembly sequences can be distinguished: a parallel sequence, and a sequential sequence.

A parallel assembly sequence can speed up a building/ disassembly process. Sequential assembly sequences create dependencies between assembled elements and makes substitution more complicated and time intensive. In-between parallel and sequential assembly/ disassembly sequences it is possible to distinguish five type of sequences: 1 gravity, (figure 53) 2. parallel, 3. closed circle; 4. interlock , 5. Sequential. (Figure 54)

Figure 53 *illustrates gravity principle of assembly. All parts can be assembled in parallel and create connection only with the main frame. (GTB Lab module)*



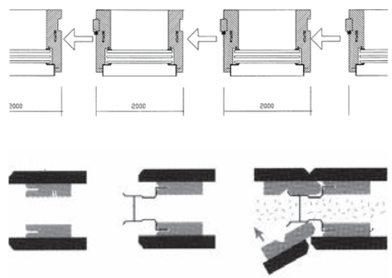
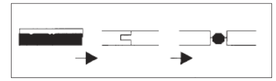


Figure 54 *five assembly principels (Durmisevic 2006)*

Figure 55 *Examples of interlock connections.*



7. CONNECTIONS

Interfaces define degree of freedom between components, through design of product edge, and specification of connection type.

In general it is possible to define three main types of connections: direct (in¬tegral), indirect (accessory), and filled.

Integral connections are connections in which the geometry of component edges forms a complete connection. Two basic integral connection types can be distinguished (i) overlapped, and (ii) interlocked. (Figure 55) Overlapped connections are often used as connections between vertical external façade components, or between vertical and horizontal components. Their disassembly depends on the type of material used in the connection, assembly sequences, hierarchical position of the components, and their relations with other components. An interlocked connection is an internal connection in which component edges are shaped differently. Here, the shape of the edges allows only for sequential assembly.

Accessory connections are connections in which additional parts are used to form the connection. Two types of connections can be distinguished: inter¬nal, and external. The internal type incorporates a loose accessory that links components. The accessory is inserted into the components. The connection possesses the advantage of an identical edge shape to the components. Disman¬tling of such connections can be difficult because of the sequential assembly sequences. The accessory external joint makes dismantling easier, with applied cover strips, or with a combination of frame and cover strips.(Figure 56)

Filed connections are connections between two components that are filled with chemical material. Assembly of such components is labor intensive. They can be welded connections between metal plates, between beams and columns, or can be connections between concrete floor panels, or bricks etc. Disassembly of such connections is often impossible, or it requires development of special deconstruction technologies as for example laser technologies.

Two main criteria for design of decomposable connections are:

1. Elements/components should be kept separated, to avoid penetration into other components or systems, and
2. Dry-jointing techniques should replace chemical techniques.

These conditions should be applied to all levels in a building. In this way all building systems become demountable, each component and element is replaceable, and all materials are recyclable.

Disassembly characteristics of a connection depend on:

- the number of connection devices,
- the type of the material used in connection,
- the form of a component's edge and
- The existence of an intermediary for separation of elements

In the range from fixed to reversible seven connection types can be distinguished. (see figure 57)

Type I – Direct chemical connection- two materials are permanently fixed by chemical connection. (no reuse or upcycling)

Figure 56 *Examples of accessory connections.*

Type II – Indirect connection with irreversible chemical connection which is stronger than the connected elements/materials/products

Type III - Direct connection with reversible chemical connection. Two elements are connected with softer chemical substances which can be removed or delaminated (reuse by refurbishment is possible)

Type IV – Direct insert connection. Two elements are connected by planed insertion of accessories into the element. (the element is weekend after disassembly)

Type V – Direct connection with mechanical fixing devises. Two elements are connected with mechanical connection which can be removed without damaging the elements. (Reuse and reconfiguration/adaptability is possible)

Type VI – Indirect connection via dependent third component. Two elements are separated with third element/component, but they have dependence in assembly reuse is partly possible)

Type VII – Interlock connection. Two elements are connected without being damaged by fixing devises (direct reuse and reconfiguration/adaptability possible)

Type VIII – Intermediary connection. Two elements are connected by third element using dry / mechanical connections. Disassembly of one element does not affect the other. (direct reuse and reconfiguration/adaptability are possible)

Type IX – Gravity, two elements are connected only by gravity force (Figure 57 and Figure 58)

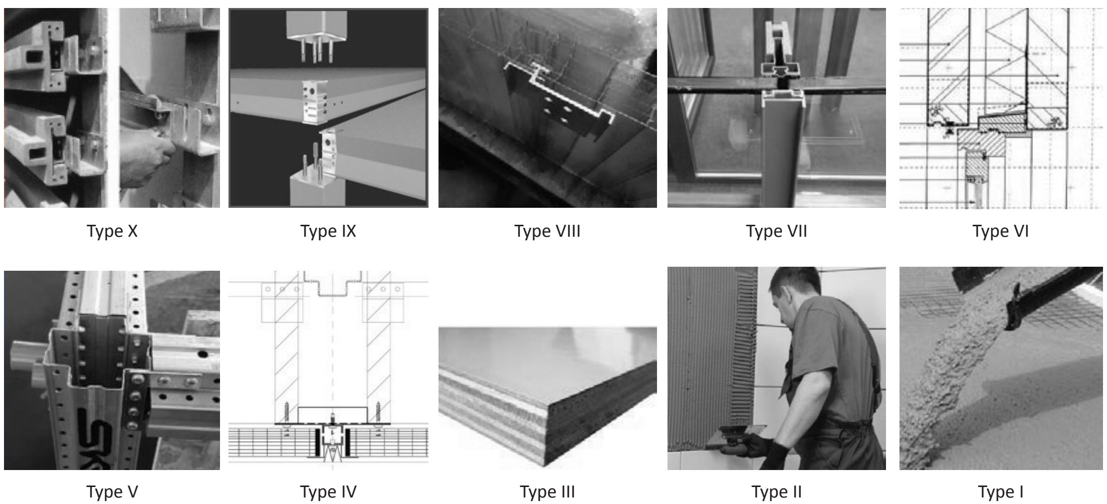


Figure 57 *Connection types are sorted out into categories covering the range form irreversible connections to reversible connections*

8 LIFE CYCLE COORDINATION OF MATERIALS

The major aspect of life cycle coordination in the assembly is to take into account the life cycle and life span of materials and products. Building materials have life cycles ranging from 5-75 years, yet frequently, assembly sequences of materials do not consider this. Materials with shorter life cycle are currently often assembled first.

However, elements, which have a long life cycle and greater dependencies in assembly, should be assembled first and disassembled last. Elements, which have short life cycle, should be assembled last and disassembled first. Two different aspects of life cycle co-ordinations are significant for transformable structures:

- assembly of materials, which have different life cycles
- assembly of materials, whose functions have different life cycles.

OVERVIEW OF REVERSIBILITY

When analyzing eight design aspects and their sub aspects a reversibility profile of building/system/ component structure can be developed which gives a first indication of possible improvements of the design in order to provide higher structural reversibility.

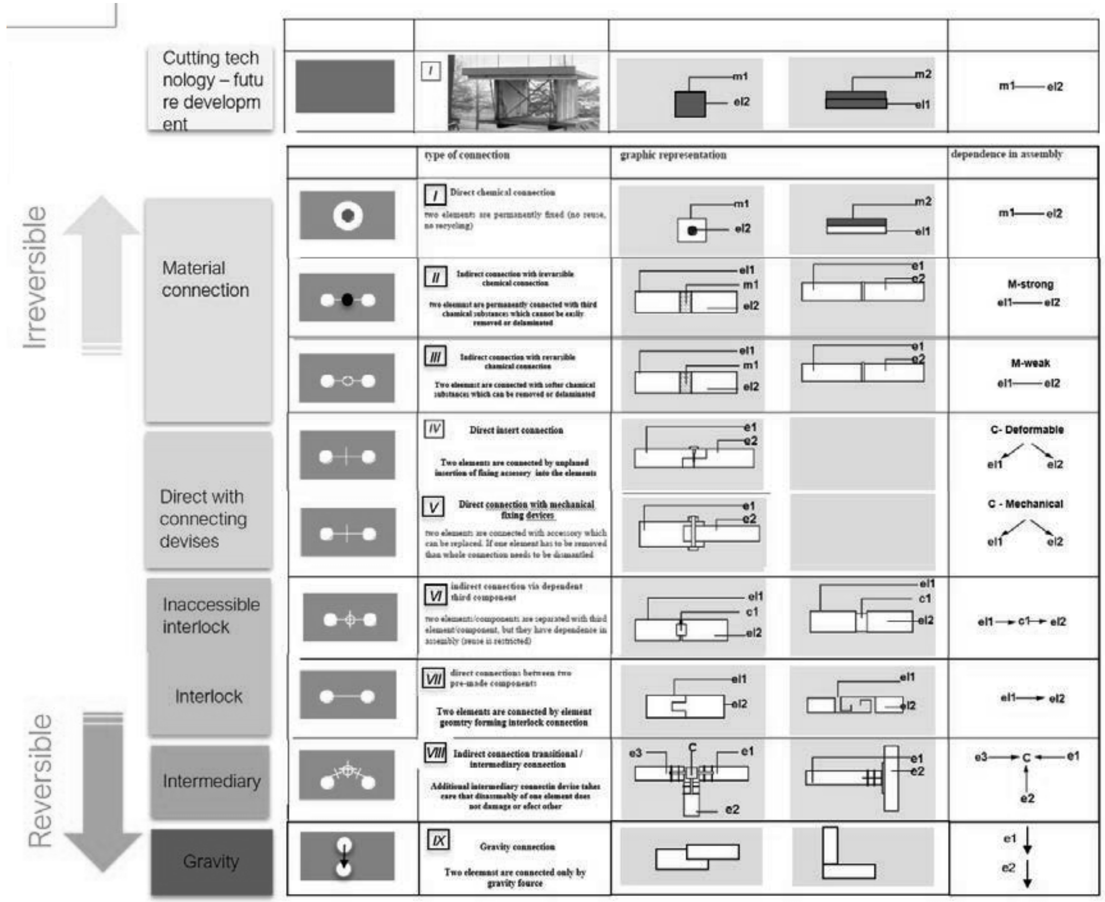


Figure 58 Ranking the connection types form reversible to irreversible

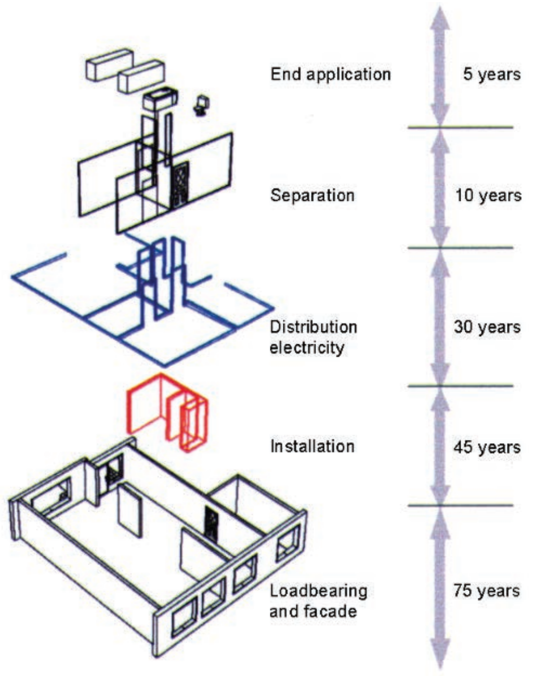
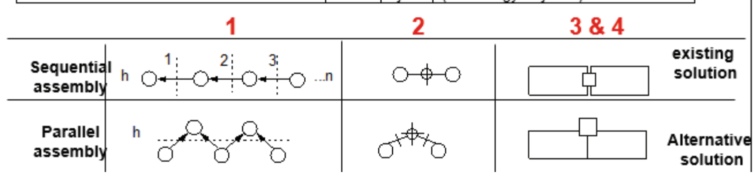


Figure 59 *overview of hierarchy of type layers following the requirement of spatial flexibility within apartment*

nr.	Design for Disasembly Aspects	nr.		Determining Factors
1	FD (Functional decomposition)			
		1.1.	fs	(functional separation)
		1.2.	fdp	(functional dependence)
2	SY (Systematisation)			
		2.1	st	(structure of material levels)
		2.2	c	(type of clustering)
3	BE (Base elements)			
		3.1	b	(type of base element)
4	LCC (Life cycle coordination)			
		4.1	ucl	(use life cycle coordination)
			tcl	(technical life cycle coordination)
			s	(coordination of life cycle and size)
5	RP (Relational pattern)			
		5.1	r	(type pf relational pattern)
6	A (Assembly process)			
		6.1	ad	(assembly direction)
			as	(assembly sequences)
7	G (Geometry)			
		7.1	gp	(geometry of product edge)
		7.2	spe	(standardisation of product edge)
8	C (Connections)			
		8.1	tc	(type of connections)
		8.2	af	(accessability to fixings)
		8.3	t	(tolerance)
		8.4	mj	(morfology of joints)



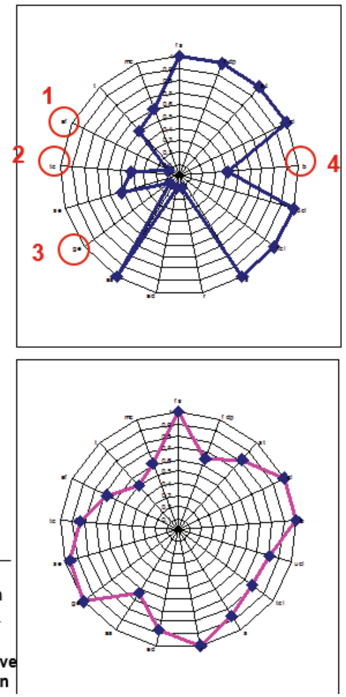


Figure 60 *overview of 8 indicators and their sub indicators as a mean to support design process towards design of reversible building solutions and technical design phases will be defined. Reuse potential assessment of the preliminary design solutions will be integrated into CBA tool in collaboration with WP5A1.*

CASE STUDY 1
REVERSIBILITY OF A NEW BUILDING
GREEN TRANSFORMABLE BUILDING LABORATORY

Heerlen NL

Green Transformable Building Laboratory (GTB Lab) is an unique European Laboratory introducing a systemic shift in the building sector. A new philosophy of waste being considered a design error.
GTB Lab will be built under the umbrella of IBA 2020 as an important part of the Heerlen circular building centre site.

By designing for circular value chains buildings will continuously increase their value. These dynamically and flexibly designed buildings are key to a circular economy. Instead of being to-be waste, buildings will function as banks of valuable materials. In this context new business models will be developed to enable the shift toward a circular economy.

By building the GTB Lab, new concepts and production processes for transformation and re-use of buildings as well as building parts will be researched, tested and presented.

GTB Lab aims to demonstrate that waste generated from changing buildings, can be eliminated or can be reduced by at least 90% using upgradable modular and exchangeable components. The other objective is to demonstrate that by GTB approach, the use of virgin materials will be reduced by at least 70%.
GTB lab will be a dynamic multipurpose structure. As laboratory that is investigating and testing dynamic green and circular concepts GTB Lab will be changing its form and function once a year.
It is designed to accommodate changes from office building into apartments and public building without demolition activities.
To set up this dynamic structure that will

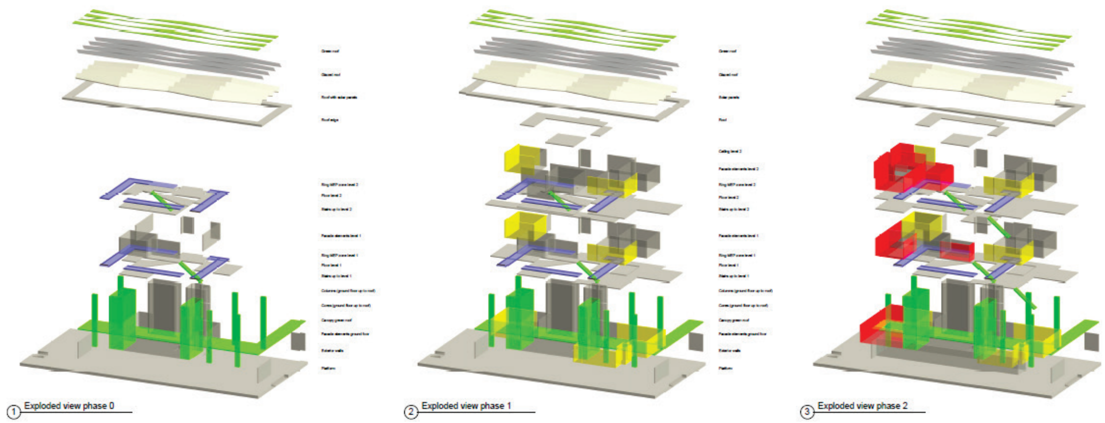


Figure 61 *Different stages of GTB Lab transformations are presented with different colours*

GTB Lab spatial requirements

	Scenario 0: Core/Carrier of tranformation model			Scenario 1: Education and research facility for dynamic and circular buildings			Scenario 2: Education and research facility for dynamic and circular buildings			Scenario 3: Education and research facility + office hub for dynamic and circular buildings + apartments			Scenario 4: Education and research facility		
	Function	**nr**	**m2**	**Function**	**nr**	**m2**	**Function**	**nr**	**m2**	**Function**	**nr**	**m2**	**Function**	**nr**	**m2**
VARIABLE				teamwork/mini classroom space	1	30	teamwork/mini classroom space	2	30	teamwork/mini classroom space	2	30	teamwork/mini classroom space	2	30
							office space	2	15	open office space for 20 work places	1	160	office space	2	15
	Subtotal		*0*	*Subtotal*		*30*	*Subtotal*		*90*	*Subtotal*		*220*	*Subtotal*		*90*
	vertical communication	1	30	vertical communication	1	30	vertical communication	1	30	vertical communication	1	30	vertical communication	1	30
	Subtotal		*30*	*Subtotal*		*30*	*Subtotal*		*30*	*Subtotal*		*30*	*Subtotal*		*30*
				apartment/studio with possible integration into one and extendibility in the second phase to 155m2 (internal transformation scenarios of appartment units)	2	35	senior appartment (internal transformation scenarios of appartment units) (1st/2nd floor)	1	35	senior appartment (internal transformation scenarios of appartment units) (1st/2nd floor)	1	70	senior appartment (internal transformation scenarios of appartment units) (1st/2nd floor)	2	70
							family appartment (internal transformation scenarios of appartment units) (1st/2nd floor)	1	120	family appartment (internal transformation scenarios of appartment units) (1st/2nd floor)	1	120	family appartment (internal transformation scenarios of appartment units) (1st/2nd floor)	2	120
	Subtotal		*0*	*Subtotal*		*70*	*Subtotal*		*155*	*Subtotal*		*190*	*Subtotal*		*380*
FIXED	public lounge (meeting, lecture, exhibition) with attached snack, coffee, copy, wifi facility	1	70	public lounge (meeting, lecture, exhibition) with attached snack, coffee, copy, wifi facility	1	70	public lounge (meeting, lecture, exhibition) with attached snack, coffee, copy, wifi facility	1	70	public lounge (meeting, lecture, exhibition) with attached snack, coffee, copy, wifi facility	1	70	public lounge (meeting, lecture, exhibition) with attached snack, coffee, copy, wifi facility	1	70
	Subtotal		*70*	*Subtotal*		*70*	*Subtotal*		*70*	*Subtotal*		*70*	*Subtotal*		*70*
	technical spaces including vertical installations	1	20	technical spaces including vertical installations	1	20	technical spaces including vertical installations	1	20	technical spaces including vertical installations	1	20	technical spaces including vertical installations	1	20
	storage	1	10	storage	1	10	storage	1	10	storage	1	10	storage	1	10
	toilet groups	2	15	toilet groups	2	15	toilet groups	2	15	toilet groups	2	15	toilet groups	4	15
	green garden 1st floor			green garden 1st floor			green garden 1st floor			green garden 1st floor			green garden 1st floor		
	energy/climate roof			energy/climate roof			energy/climate roof			energy/climate roof			energy/climate roof		
	water storage below deck			water storage below deck			water storage below deck			water storage below deck			water storage below deck		
	Subtotal		*60*	*Subtotal*		*60*	*Subtotal*		*60*	*Subtotal*		*60*	*Subtotal*		*90*
	Total		**160**	**Total**		**260**	**Total**		**405**	**Total**		**570**	**Total**		**660**

support multiple transformations (as defined by spatial requirements), and upgrade without waste, the first phase of the development of GTB Lab was focused primarily on the development of the core of the GTB Lab.

The **Core**, this most fixed part of the building, needs to have capacity to facilitate transformation from one use scenario to another without demolition and waste creation. The Core is multifunctional integrated base element of the transformable building. The Core needs to encapsulate a minimum needed to provide structural stability and facilities climate, energy and comfort concept for different use scenarios that will be investigated within GTB Lab. It should have capacity to support multiple transformations during the use phase of the building.

Therefor the first development phase of the GTB Lab is organized around the construction of the integrated base element (Core) of GTB Lab, a minimum needed to provide for structural stability and facilitate climate, energy and comfort for different future use scenarios that will be investigated. The vision of the future buildings which is upgradable without material degradation and in which natural and humans systems empower each other has been a guiding principle for design of GTB Lab. For that reason, besides support of building transformation without waste, the core has to provide sufficient daylight and natural ventilation to all emerging spaces as well as stability to support changeable loads and climatic requirements when changing function from office to housing and when changing the form. This has resulted into a decentralised vertical core structure with provisions for horizontal installation distribution ring which is connecting four vertical installation ducts (Figure 62).

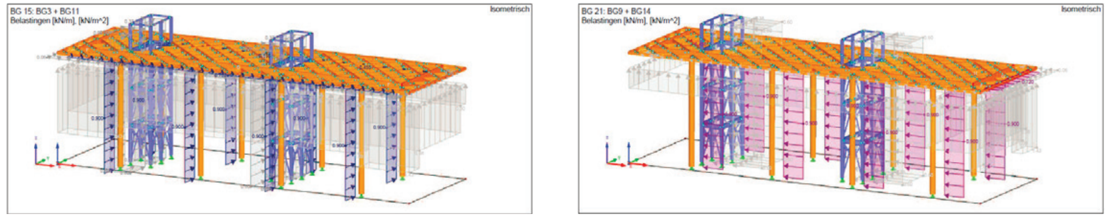


Figure 62 *Analyses of impact of different load combinations on GTB Lab core elements*

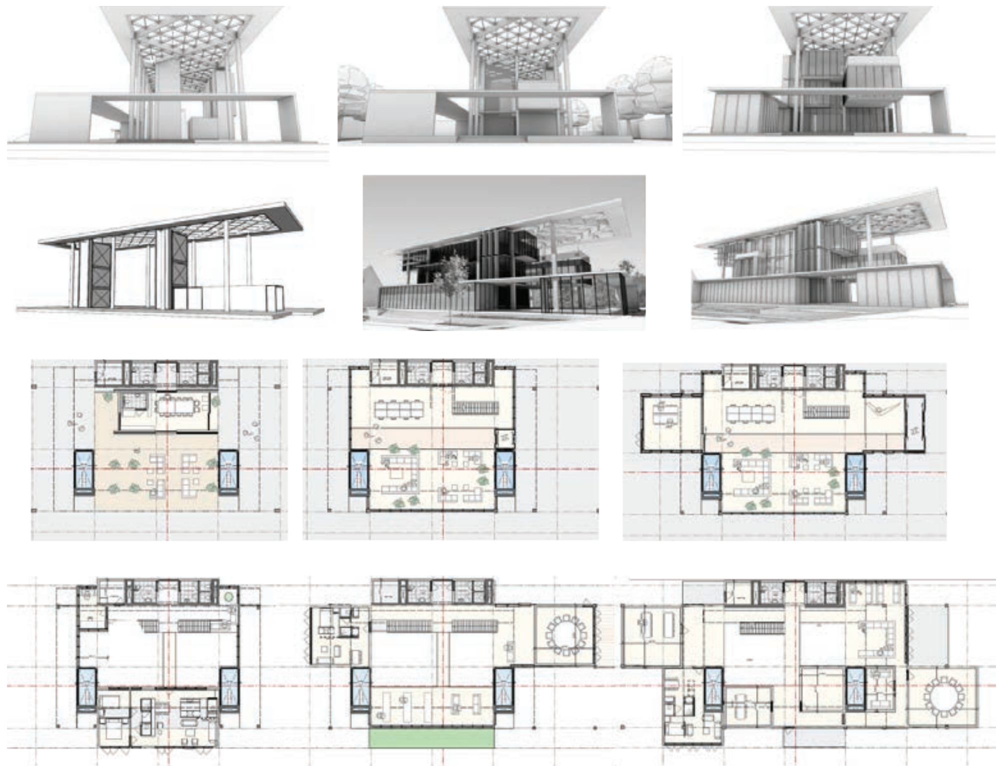
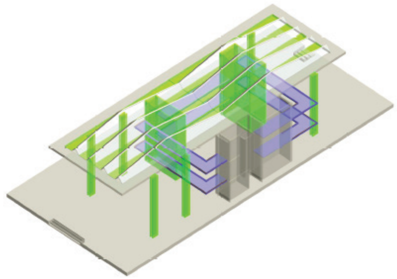


Figure 63 *Possible reversible design scenarios in the Green Transformable Building Laboratory (GTB Lab)*



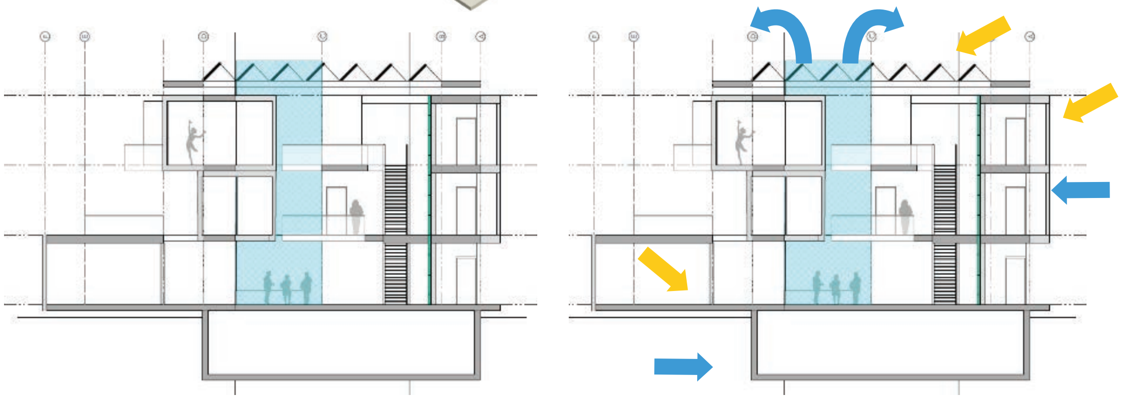


Figure 64 *Air and light flow diagrams.*

Figure 65 *Green Transformable Building Laboratory (GTB Lab)*

Design and engineering team has completed preliminary design for the first phase while mapping multiple design scenarios that have shaped the transformation model of GTB Lab and its potentials and boundaries considering its transformation. The design of the Core for GTB Lab took into consideration changes in the size of spaces as well as changes of functionality of spaces and the position of spaces. Programming diagrams have been made in order to communicate the transformation requirements per floor to the engineering team.

The two air and light chimneys and linear service core are connected by a horizontal ring that distributes installation services between the vertical cores. This is illustrated on the 3D model above, showing blue horizontal elements that form a ring around vertical core elements.
The blue distribution network is multifunctional and has loadbearing capacity as well. Besides distributing installations in between vertical installation ducts the horizonal ring is designed to host extendable spatial units on both sides.

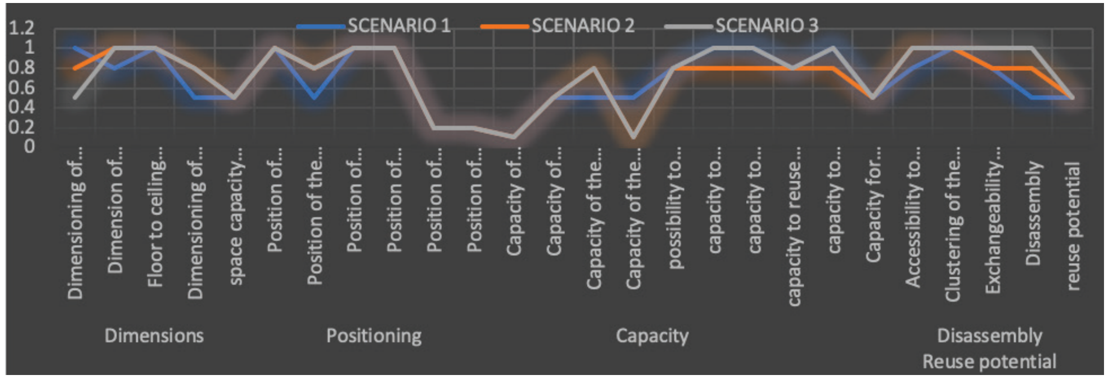
As a principle, all spatial units of the GTB Lab will receive fresh air directly form outside while the units will be ventilated through the air ducts. Air duct is at the same time providing natural light to all spaces and units (Figure 64).

Such core enables functional changes of units and possibility to the installation services to be plugged into the horizontal ring and get connected to the main infrastructure of the building. At the same time modular reversible unites can also be developed as independent from the main climate and energy net of the GTB Lab.

ANALYSIS PHASE

During the design of GTB Lab number of lay out options have been investigated and their transformation capacity has been analysed using transformation indicators developed by BAMB Reversible Building Design.

Scheme results (Figure 65) have been done by students of architecture following International Design studio 2018. Their schemes indicated transformation potential of GTB Lab in relation to the three investigated use scenarios housing, offices and education. Transformation indicators are ranged from 0,1 to 0,9. Ranging corresponds to the (high-low) effort needed to transform GTB Lab to one of the three scenarios.



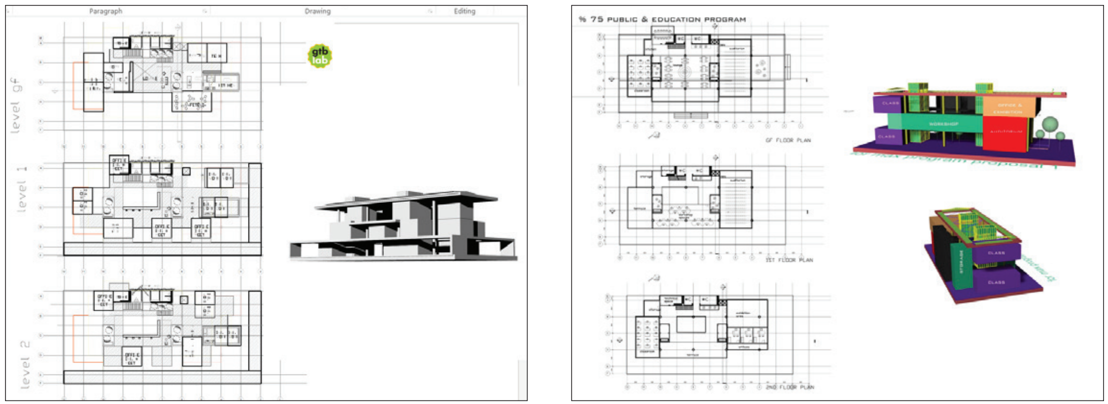


Figure 66 *Transformation potential of the GTB Lab in three scenarios.*

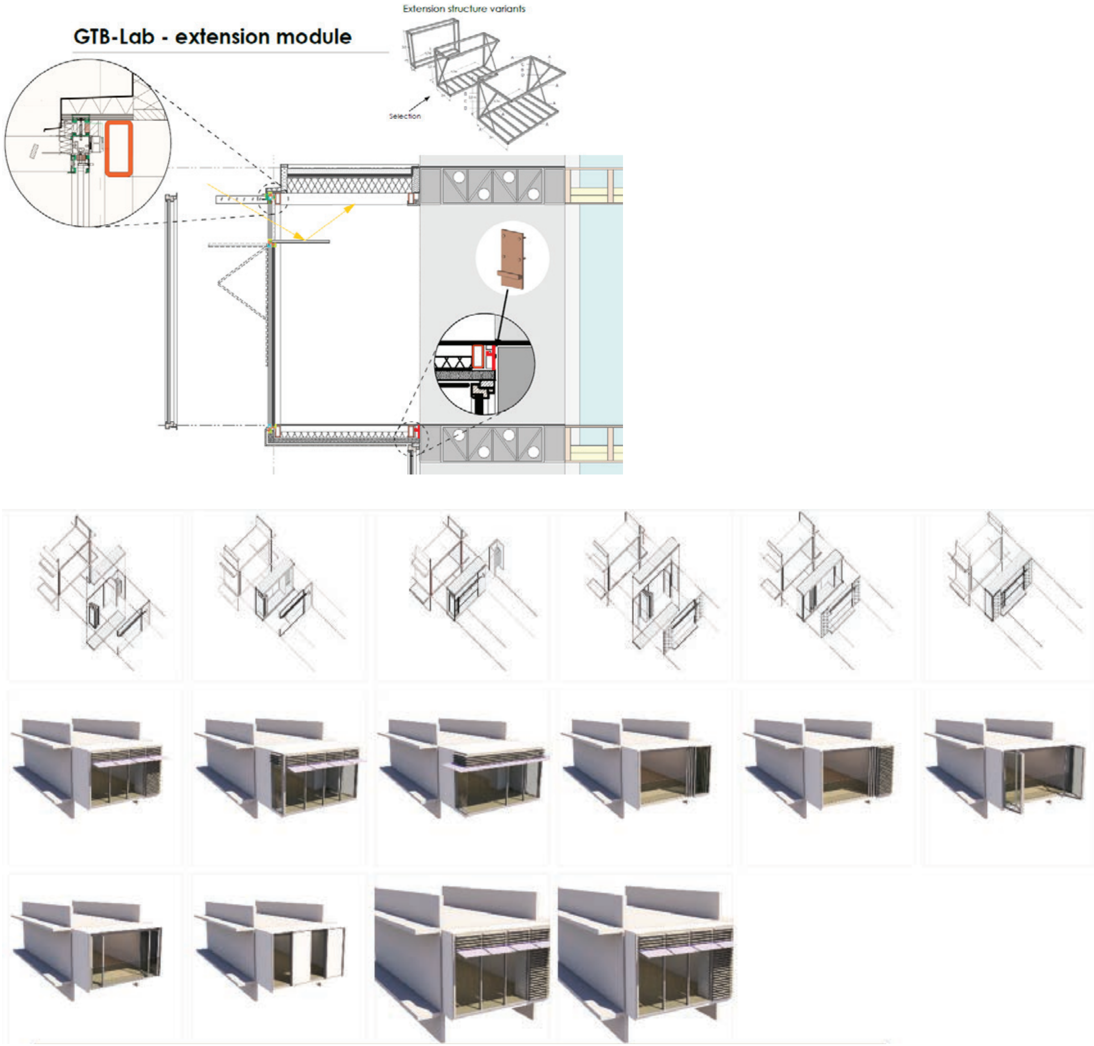


Figure 67 *Multiple spatial and material use scenarios of GTB Lab*

CONCLUSIONS

Design of transformable building leans on understanding the potential use scenarios in the future and linking them to the technical compositing of building. Each set of use scenarios will result in different hierarchy and technical compositing of building structure.

However, it is not possible to predict the future, and the ideal transformable building does not exists. The intelligence of the design will not be linked to what building is, but rather what building can do. This will determine its future value. Design becomes partly invisible as it becomes part of the invisible force that makes building being updated following its users' needs without being demolished along its use life. This brings the design focus to the core of the building; i.e. the more stable parts of the building that will have basic capacities to support future transformations. In order to define a design brief, the client will need to take more effort in understanding the future options of the building he/she is commissioning, in terms of use scenarios of the space but also of use scenarios of materials. To do so the client needs to be aware of different value propositions behind the reusable components of reversible buildings as well as the business models behind a high transformation capacity and reuse potential.

GTB LAB MODULE

1st Reversible GTB Lab module with integrated PV in triple glass facade

GTB Lab circular module has been developed with full reversibility in mind and aiming at high reuse potential of all building parts.
four reversibility scenarios have been fully investigated and applied.

1. **Reversibility on module level** including replicability of façade, roof, floor as for example using the façade caseates to create a floor/terrace which took place during the modules and extendibility of the modules transformation.

2. **Reversibility on component level**, including reconfiguration of floor, roof or facade cassette by transforming the door into a window or a shelf.

3. **Design - production measurement** coordination to eliminate 98% of production waste.

4. **Replicability/transportation of 3D module** and extendibility of the modules





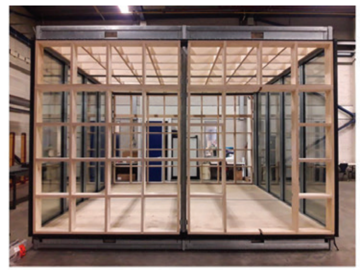





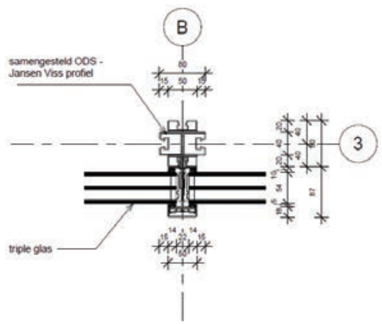


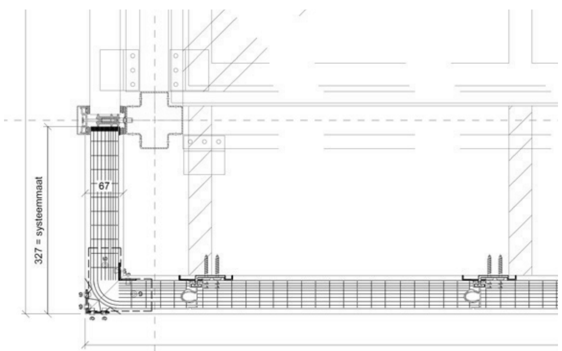
Figure 68 *Assembly of GTB Lab module*

GTB LAB MODULE

Architect
Elma Durmisevic, 4D architects

Industry Circular Building _ GTB Lab consortium
Kloeckner Metals ODS Nederland, Ron Jacobs, Paul Penners, Michiel van Dooren
Skelet: Ivo Swenters
Pilkington Nederand B.V. Marcel Ribberink
TheNewMakers, Pieter Stoutjesdijk
Rodeca, Peter Lindeman
Ammanu, Niels Leijten





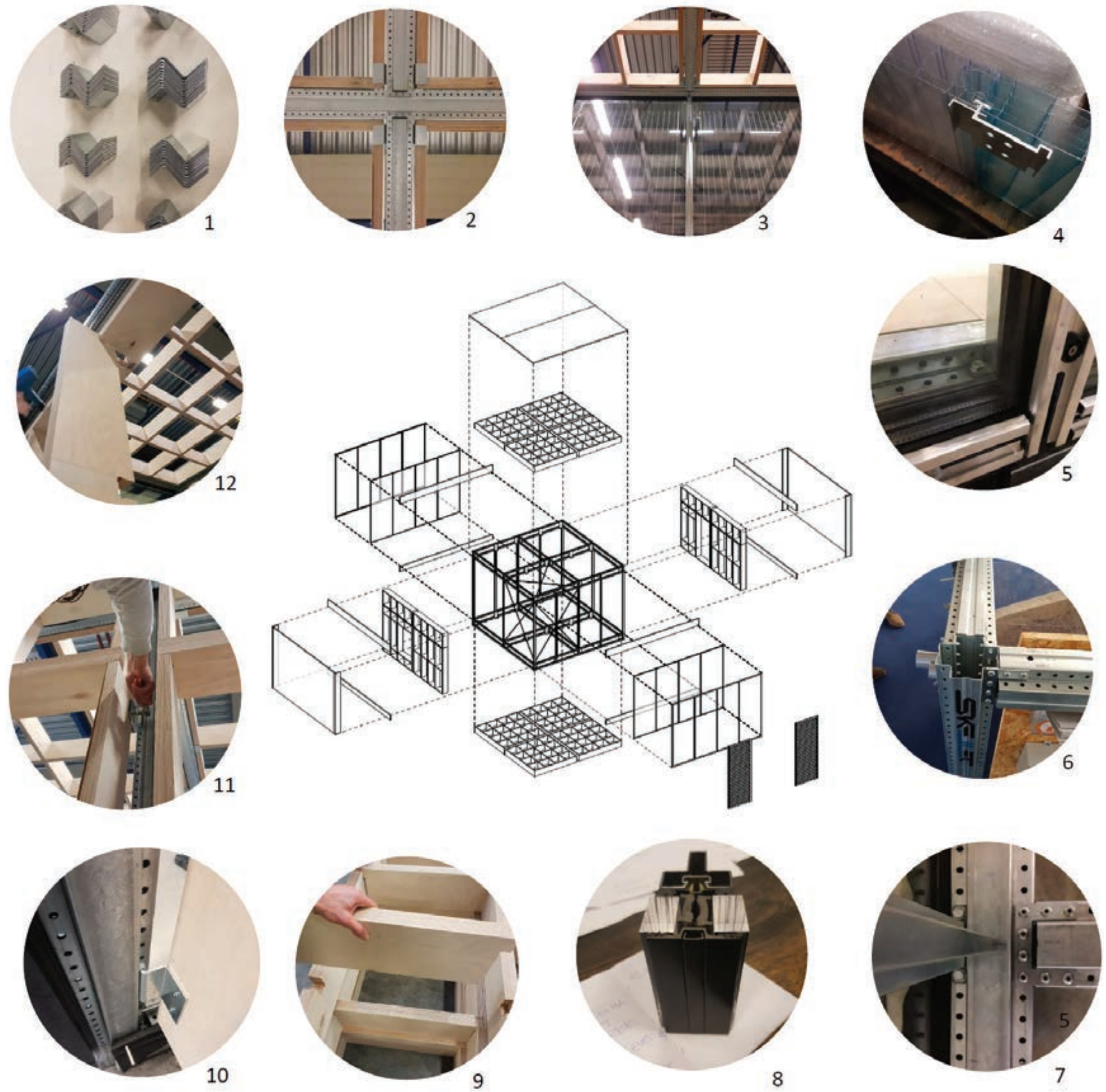


Figure 69 *Assembly details of GTB Lab module*

Figure 70 *Transformation and extension of GTB Lab module*

CASE STUDY 2
REVERSIBILITY OF AN EXISTING BUILDING GREEN DESIGN CENTER

Mostar BA

The remains of a military camp, placed by the Austro-Hungarian government on the outskirt of Mostar in the 1880's, are nowadays situated on the crossroad of the city. The former army base forms an interface between the historic old city fabric and the new city developments, while becoming a true bridge maker between the past and the future and a bridge between living, recreation and business.

The aim of the project is to transform the, at the moment, devastated former military zone into a new centre of innovation and creativity. The centre shows Mostar's potential to make a transition towards a green circular city. It utilises natural and human social capital and creativity creating a new place of inspiration. Young designers and engineers get a space and opportunity to work together on envisioning the future of their city and reversing the trend of migration.

Green Design Center (GDC) is envisioned as an open meeting place and aims at:

- promoting and showcasing new product and business solutions as result of co-creation and collaboration between creative, production industry and knowledge institutions
- bring together Green design Innovation, knowledge institutions and manufacturing Industry
- Open day GDC activities for inhabitants and visitors. This will bring green design and their innovative solutions and practical implementations closer to citizens and visitors.

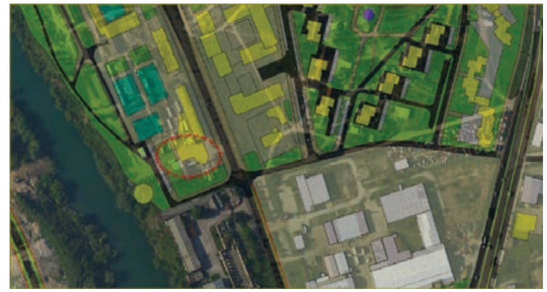


***Figure 71 Bottom**: location of Green Design Center between historic and new city developments **Top**: Masterplan from year 2000*

Figure 72 *The remains of the Austro-Hungarian army base*

- work together with schools for children with disabilities and present their work during international Green Design Events and open days.
- community building will be reinforced trough urban gardening and permaculture urban gardens

GDC promotes methods to transform and revitalise historic buildings and site by reusing existing structure/ fabric as a socio-cultural and material backbone that sustains the identity and the meaning for the new dynamic programs. GDC building itself is a true showcase of such approach. It provides place for community involvement through co-creation sessions. It promotes eco urban / permaculture development / local food production. It promotes use of green on and round the building for water absorption, cooling effects and air quality by different measurements taking place in and around the GDC.

It brings awareness about waste and construction waste, and necessity to develop concepts for use of natural materials in closed loops eliminating waste by design. It promotes transformation and reuse of buildings in contrast to demolition and concept of seeing all buildings as material banks.
GDC contributes to developing a knowledge platform and testing / monitoring LAB environment that will support decision making process and strategy planning for Sustainable Cities and Communities. It provides expo space showcasing circular building/ housing solutions using local materials and energy sources.

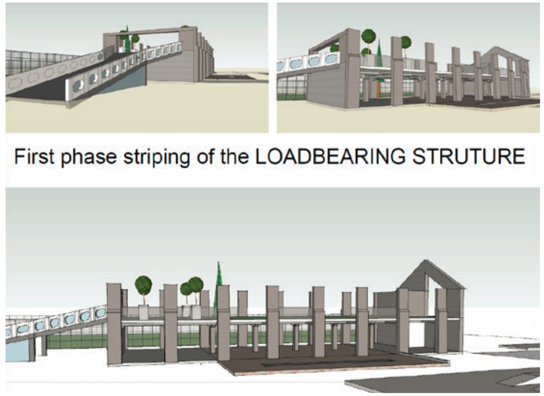
Location preparations and existing structure

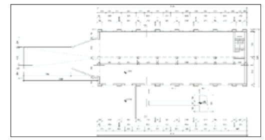
Green Design Centre is envisioned as a location that will be showcasing principles of reversible building design and circular buildings. It is also place for development of new reversible concepts with the local industry.

As such, it will be a part of a new innovation park in Mostar, where different aspects of sustainable living will be integrated such as urban faming, wind mills, open workplaces for disabled children and open expo exhibiting innovation sustainable concepts.

GDC will be a flexible building that explores strategy for reversible interventions in a way that can extend the use of existing structural elements and create new space by reusing its capacity. Building will be developed with potential to be extended and upgraded. Main spatial flexibility deals with internal flexibility and space enlargement. Technical requirements are related to technical system that will support spatial flexibility while eliminating waste and supporting material circularity. Requirements as extendibility and reconfiguration are on the top priority. Innovation park around the building has been design with the same grid (3,1 m) in order to unable circularity of materials used in the building and in the park. Parts of the modules from the building can be replaced to the innovation park and form a pavilion and other way around.

Detailed structural analyses of the existing structure have been finalised. This has changed previous assumptions about the existing structural elements at some points. The analyses indicated that main structure need to be reinforced and that the first floor is weaker than expected. This has changed some parts of the strategy and initial approach to transformation and planning.





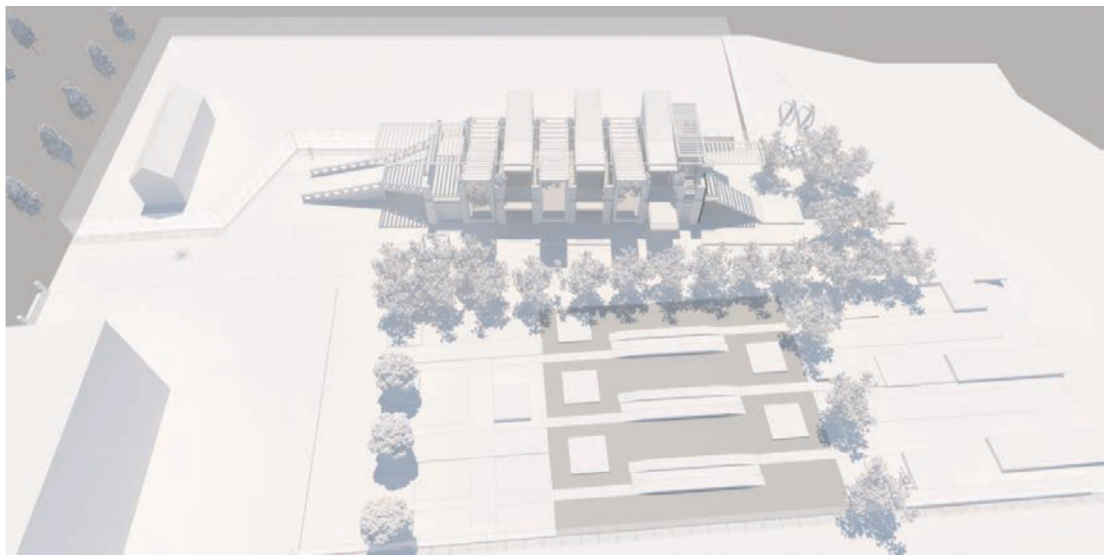
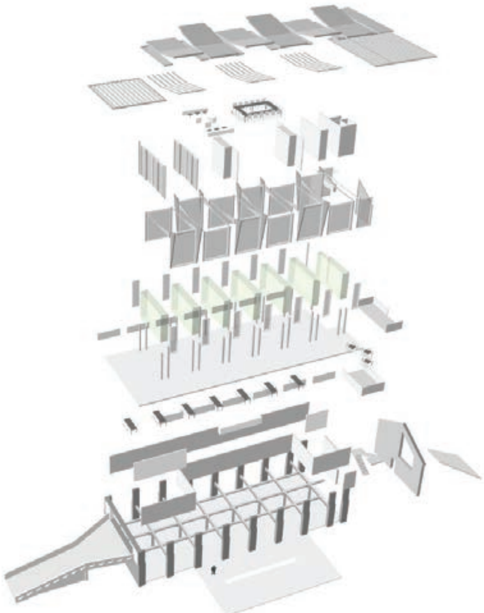
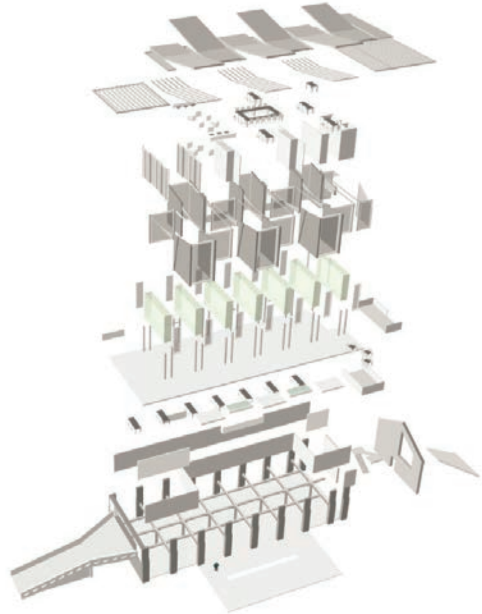


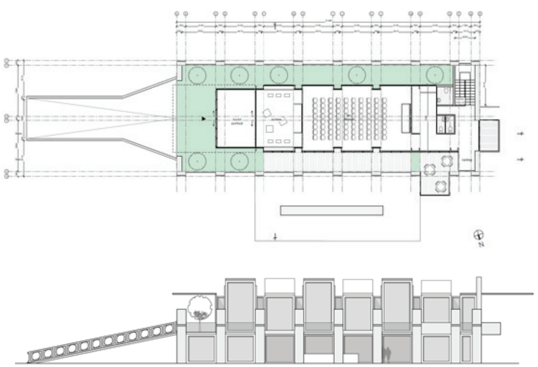
__Figure 73__ A new Innovation Park in Mostar reusing the reinforced loadbearing parts of the existing structure





minimum scenario

maximum scenario



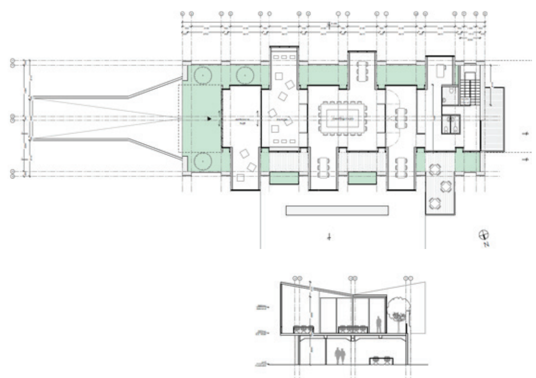
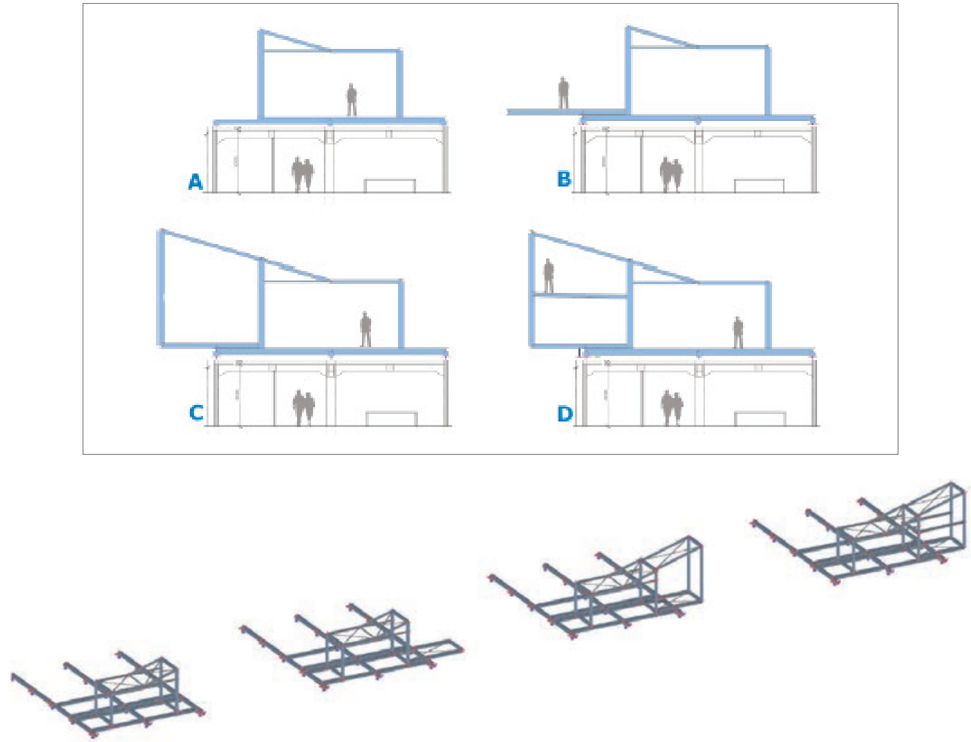


***Figure 74 Left** first construction phase **right** second construction faze extending the volume*

Design

The first construction phase has focus on partial demolition of the existing structure and its reinforcement. Due to a weak horizontal parts of the existing structure (beams and floor) only vertical elements will be used in the new structure. A steel frame will be created as a raised floor and intermediary between the old and the new part of the building structure and installation distribution network. The core of the GDC will be formed by a 3D steel frame which will house future extension units. Each 3D steel frame will be accommodated with an installation module containing all necessary installation services. Such approach makes it possible to extend the structure by adding new 3D frames with associated installation modules. The main installation core contains two horizontal distribution lines and 3dimensional portals with installation services being intermediary between the two modules.

Following this design approach it is possible to transform, extend and update the building structure by exchanging the modules. The design took into consideration exchangeability of office modules, exhibition and housing modules. Furthermore all subsystems of the modules as facade, roof, floor, etc. is reversible and can be replaced and modified according to the requirements of the new use.



Today

Tomorrow

Figure 75 *New steel frame as an intermediary between the old and the new part of the building structure and installation services.*

Figure 76 *Transformation scenarios*

Prototyping of GDC is an addressed issue of reversible facade design with high reuse potential of building elements and components. Also, high energy efficiency is set up as an ambition. Focus of the development was put on more bio-based solutions and use of local materials, as wood and sheep wool. As part of an exploration of the reversible façade system, we construct a prototype of a façade with interchangeable modules which can be replaced and adjusted to different requirements of the façade in the future. Number of transformation scenarios have been investigated as **(1)** transformation from housing to office **(2)** transformation from office to exhibition space. In the first scenario - a closed facade, which was providing privacy in the apartment, has been transformed into a facade with window openings required by new office space. Some of transformations are presented in the figure left.

Considering the fact that many changes of use of space have impact on the facade layout and its performance, (and that technological developments are also reflected on the technical performance of the facade), the prototype aimed at development of a facade system that can be updated while safeguarding the value of materials and their reuse potential. This has been achieved by following design principles for reversible building design developed in WP3.

Primarily focus was on

1. separation of different functions of the facade system and materialization of individual function as independent cluster of elements,
2. avoiding unnecessary damaging of elements during assembly and disassembly by positioning an intermediary element made of a material that will not brake or be damaged during disassembly and reassembly, and which will eliminate a need for additional drilling of holes for screws or bolts, which would decrease the quality of the elements,
3. increasing reuse potential of elements by applying simple strait forward generic geometries which can be applied in different products and contexts. More information is provided in D13.
4. Furthermore focus was put on bio based solutions and use of local materials as wood and sheep wool.

Figure 77 *Prototype of the steel frame*

Figure 78 *Placing reversible steel frame on the existing structure*

GDC Mostar
Sarajevo Green Design Foundation (SGDF) in collaboration with City of Mostar

Architect
Elma Durmisevic, SGDF/4D architects

Industry _ GDC consortium
ArrhiPlus,
Alfatherm,
Konstrukcije,
Atelje Z,
Ramaglas.

Partners
City of Mostar,
University of Dzemal Bjedic,
University of Mostar,
Alfatherm,
ADA.

Figure 79 *Mounting the reversible floor and roof elements on the steel frame*

Figure 80 *Green Design Center as an innovation park*

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