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WP3

Reversible Building Design

Reversible Building design guidelines

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REVERSIBLE BUILDING DESIGN GUIDELINES and PROTOCOL

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At the time of diminishing of resources and increase of environmental problems, it has become crucial to understand the capacities of buildings to transform a negative environmental impact of built environment to a positive one. The question is: how does one transform the current linear approach to design of buildings that has one 'end-of-life' option (demolition) to a circular design solution that will guarantee multiple life options of the building as well as of its systems, products and materials? This chapter looks into three dimensions of transformation (1) dimension of spatial flexibility of building; (2) dimension of technical flexibility of systems and product; and (3) dimension for material flexibility that can make a transition from a linear to circular building. Buildings designed with three dimensions of transformation open opportunities for a great palette of new value propositions of buildings and its systems, products and materials. Those buildings are called reversible buildings. Durmisevic 2017

THREE DESIGN DIMENSIONS OF REVERSIBLE BUILDINGS

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1

Reversibility of space
Adapt space



2

Reversibility of structure/
Reconfigure /upgrade structure



3

Reversibility of material/
Separate elements/ material

DESIGN PARAMETERS / ASPECTS OF REVERSIBLE BUILDING :

Project Brief definition: multiple scenarios for use of building if possible draft scheme of possible reuse options for the materials as well

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

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 from one use scenario to another without demolition and waste creation

PARAMETERS OF STRUCTURAL REVERSIBILITY/design aspects :

Functional independence

provided through separation of functions on building, system and component levels

Technical Independence

provided by minimization of relations between different functional modules and creation of structured and open hierarchy that is leaning on well defined base elements of the structure

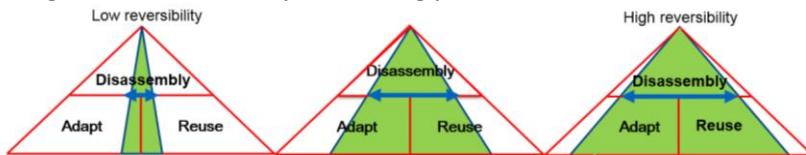
PARAMETERS OF PHYSICAL REVERSIBILITY/design aspects :

Physical exchangeability

Provided by design of demountable connections that are preventing damages of elements by considering geometry and morphology of product edge, disassembly sequences, type of connection

LEVELS OF REVERSIBILITY

'Reversibility' is defined as process of transforming buildings or dismantling its systems, products and materials without causing damage. Building design that can support such processes is reversible (circular) building design (RBD) and can be seen as key 'accelerant' of Circular Economy in construction. Reversible Building Design is therefore seen as a design that takes into account all life cycle phases of the building and focuses on their future use scenarios. 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. A key element of RBD is design for disassembly, which allows for easy modifications of spatial typologies and disassembly of building parts.



Disassembly, adaptability and reuse form the nucleus of three dimensions of reversibility and as such determine spatial and structural levels of reversible buildings.

The guidelines in this document address design aspects and protocol for reversible buildings and covers design aspects which deal with Spatial reversibility, spatial dimension and Technical reversibility which covers structural and material dimension of reversibility.

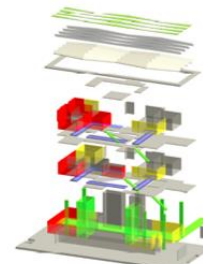
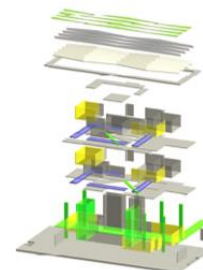
REVERSIBLE BUILDING DESIGN

Technical Reversibility

Spatial Reversibility



■ Reconfigure structure
 ■ Separate materials



■ Adapt space

INTEGRATED DESIGN PROTOCOL

Integrated Design protocol integrates aspects of spatial transformation and building level reversibility with technical aspects related to the recovery and high reuse potential of products. These have been presented in the figure below. Aspects defining the building level transformation capacity of space are part of the feasibility design phase and are being further defined during the preliminary design phase.

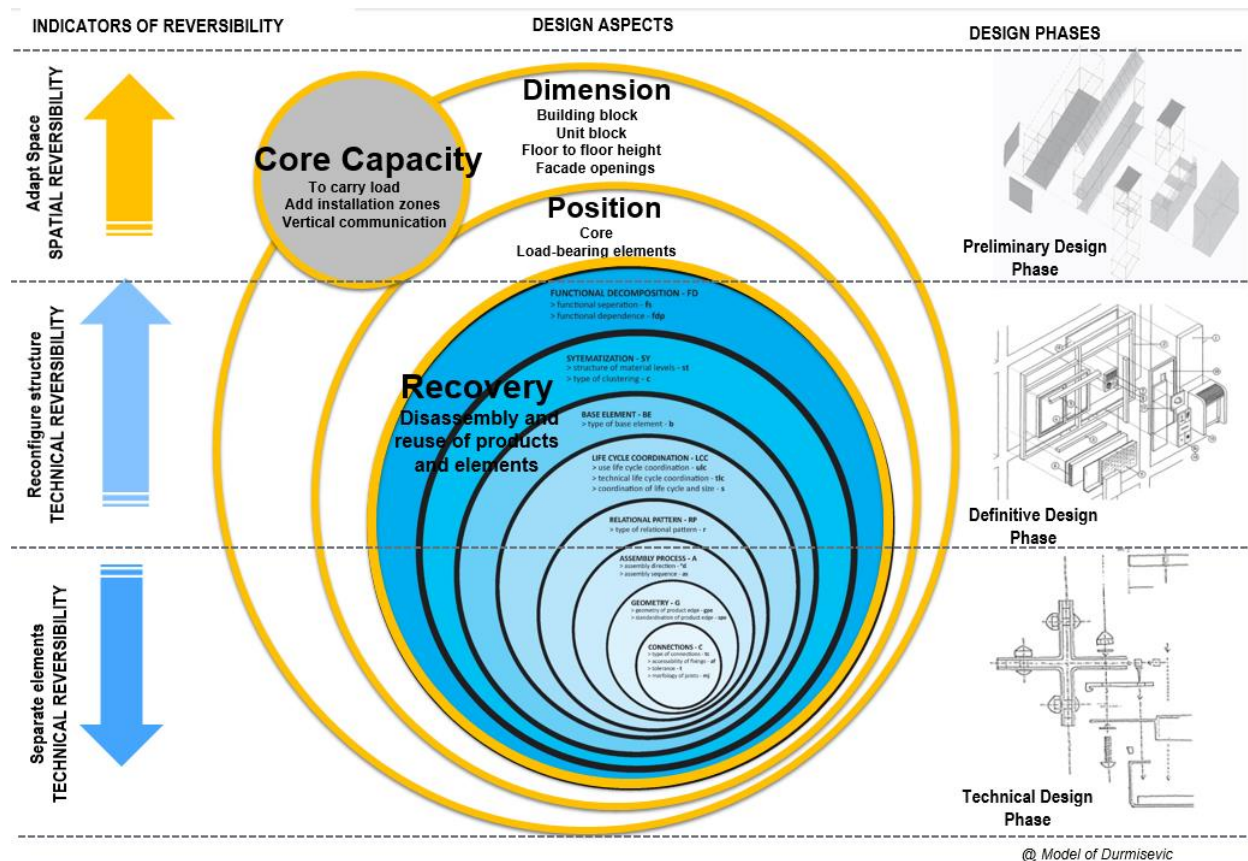


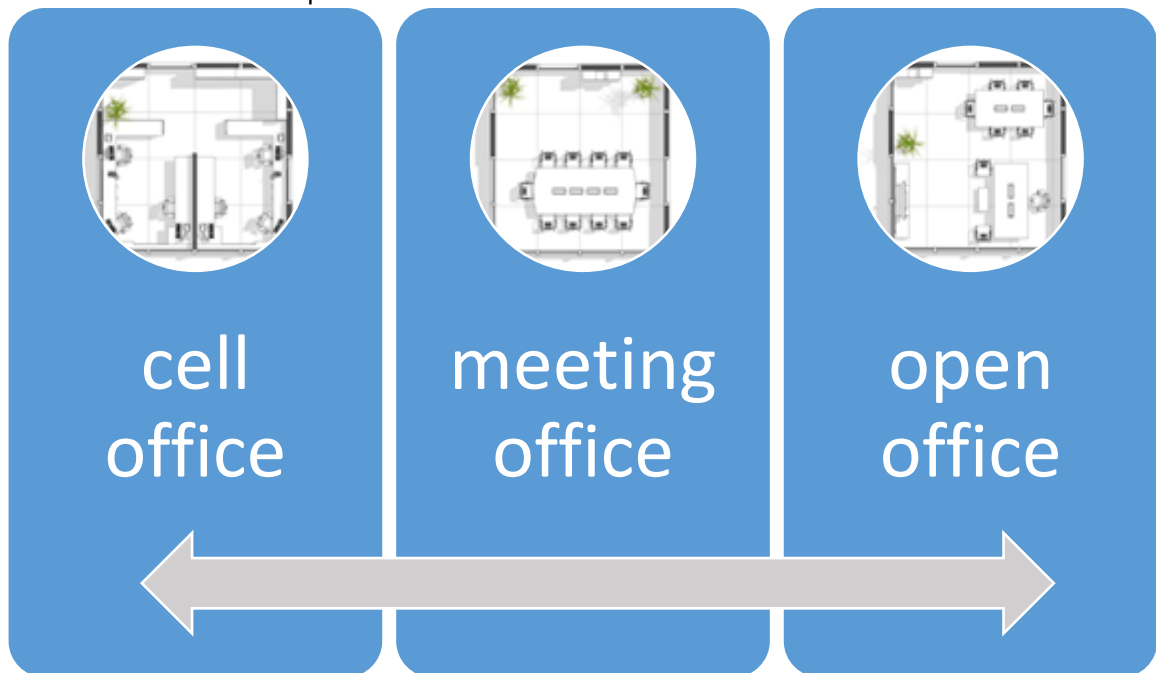
Figure : Reversible building protocol integrating spatial and technical aspects of reversibility.

SPATIAL REVERSIBILITY,

The spatial and building related transformation as a change of the building function and its impact on the building structure are analyzed during feasibility and preliminary design phase. Design process analyses the capacity of space and structure to accommodate different functions without causing major reconstruction works, demolition and material loss. The less effort needed to transform a building, the higher transformation potential it will have. The greater the variety and number of modification options (reuse options of buildings), the higher the transformation potential. Three major types of transformations are identified: mono functional transformation options, trans-functional transformation options, and multidimensional transformation options which integrate the above two as well as exchangeability and relocation (named transformable option). See below:

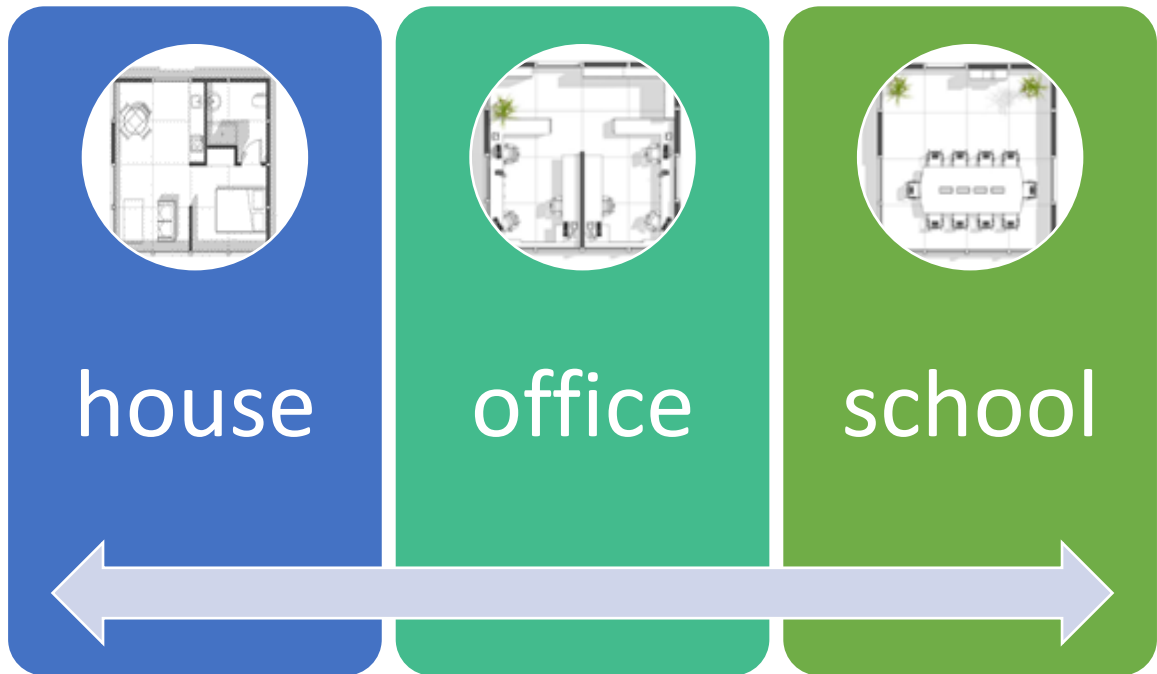
1. **Mono-functional:** transformation in mono functional context

Buildings in this category have capacity to transform 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. Or an housing block has 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. Transformable: fully transformable buildings

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



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

In that respect if building has no transformation scenarios as an option it has the lowest score. Further on the three transformation categories are defined from low transformation potential to high transformation potential as illustrated in the figure below.

Relations between the transformation potential and type of transformation are presented in the figure below.

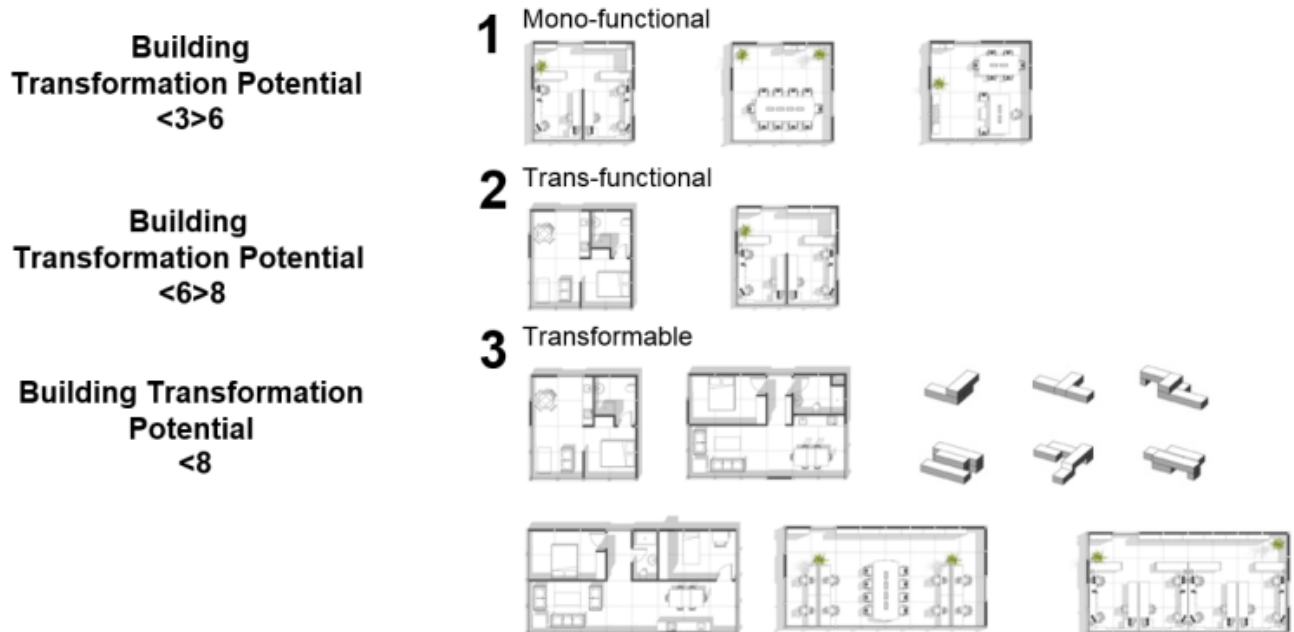


Figure: Relations between the scores and type of transformation.

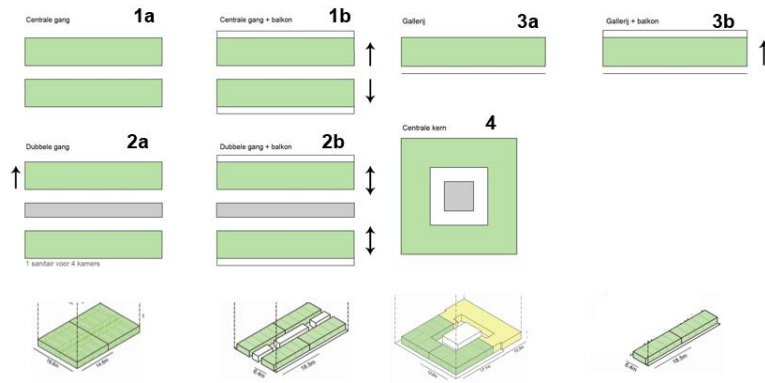
Design indicators of spatial reverisbility

DesignParameters that have impact on transofrmation potential are: building typology, dimansions 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.

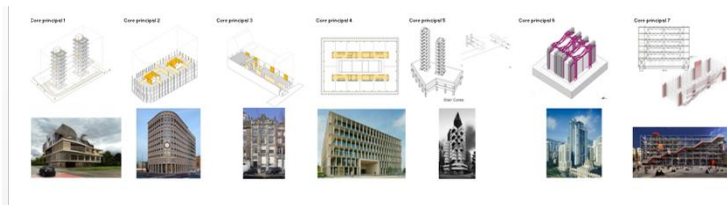
Espatailly the following combinations of the design parameter will impact the ability of building to be transofmed.

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

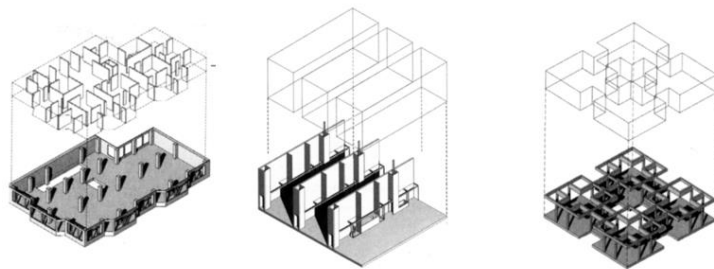
1. Topology in combination with the depth and with of the block (relation to the natural light)



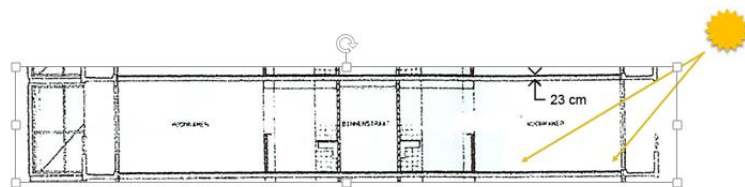
2. Typology in combination with the type and position of the core, block dimension and distances between the cores



3. Typology in relation to the core, block dimension, structural system and method of construction



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



LEVELS OF TECHNICAL DECOMPOSITION

Designations such as system, subsystem, component is relative. A subsystem at one level is a component at another level. Reversible buildings recognize three levels of technical composition/decomposition is:

- Building level represents the arrangement of systems, which are carriers of 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 materials, which are carriers of component functions, (such as bearing, finishing, servicing component) (Durmisevic, 2006).

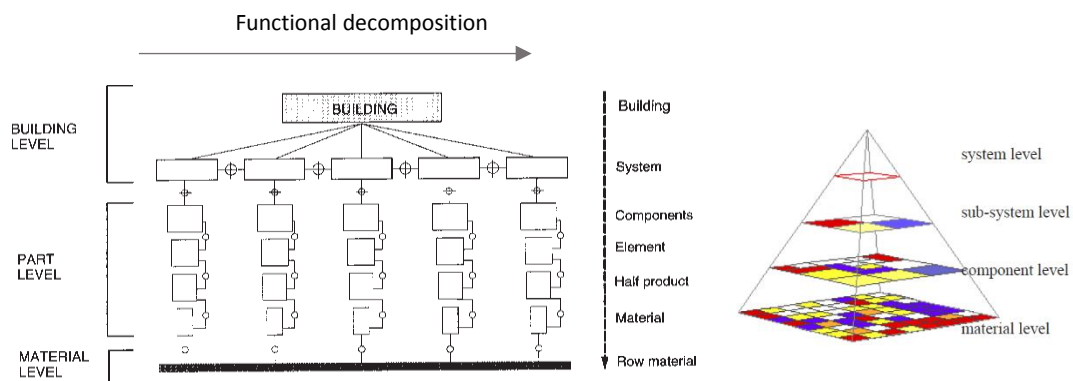


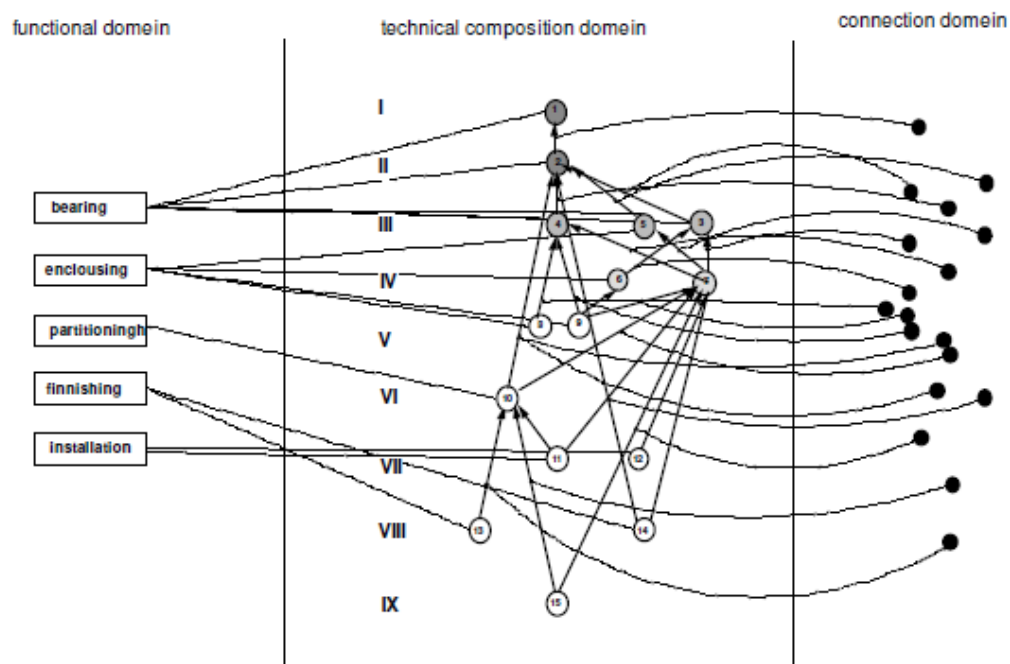
Figure: Hierarchy of levels of technical decomposition of reversible buildings (Durmisevic, 2006)

REVERSIBLE BUILDING DESIGN DOMAINS

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 materials, which have different changing rates. This domain defines functional dependences
- Technical decomposition deals with hierarchical arrangement 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.



Reversible configuration is regarded as the process of creating an arrangement from a given set of elements by defining the relationships between selected elements and their functions in a way that will satisfy requirements and constrains for disassembly, reuse and transformation.

During reversible configuration design, a designer allocates functions to a sets of elements and determines their relations. As a design activity, configuration design can be seen as an activity concerned with different relationships and interdependencies. Defined set of relations and elements 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 structure's reversibility. (Durimisevic 2006)

KEY INDICATORS OF REVERSIBILITY

Two key indicators of reversibility of building structure are Independence and exchangeability of building systems/components.

Independency

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.

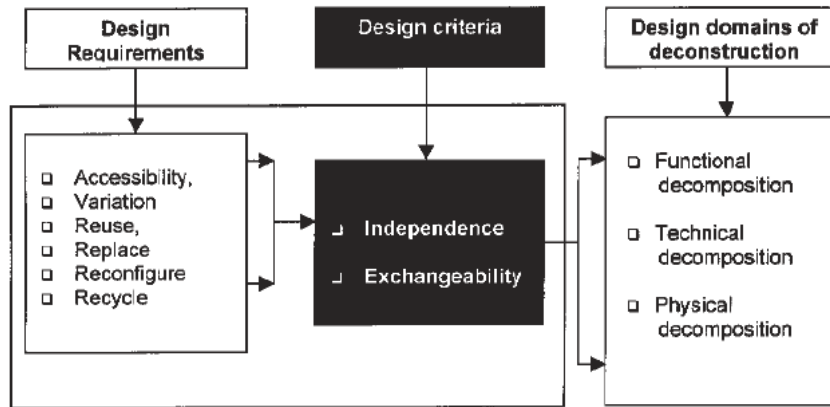
Exchangeability

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.

DESIGN PRINCIPLES FOR REVERSIBLE BUILDING STRUCTURE

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,
- reconfiguration, and
- recycling



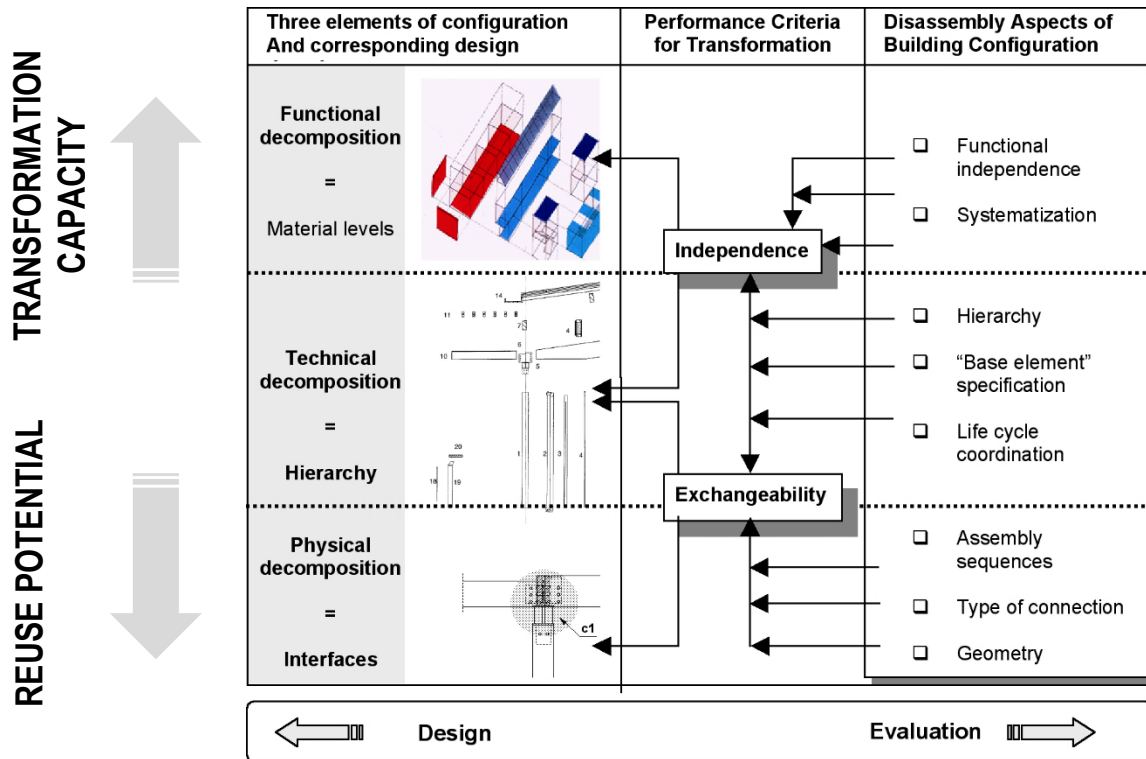
A structure can be reversed if its elements/component/systems are defined as independent parts of a building structure, and if their interfaces are designed for exchangeability. Independence of parts is determined primarily by functional design domains, which deal with design of material levels of technical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

Design aspects that have influence on decision-making during design of reversible structures.:

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, and
8. life cycle co-ordination in assembly/disassembly.

Unlike conventional structures in which design deals with functional, technical, and physical composition, the design of reversible structures considers functional, technical, and physical decomposition.

Depending on the view we are looking at reversible structure (whether with the focus on reuse of elements or focus on transformation of structure) impact factors of the criteria measuring functional, technical and physical dependences will differ. (see figure billow)



REVERSIBLE BUILDING DESIGN PROTOCOLS

1. FUNCTIONAL DECOMPOSITION

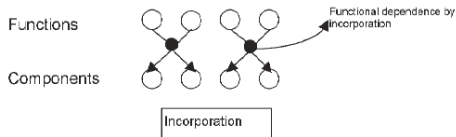


Functional Separation

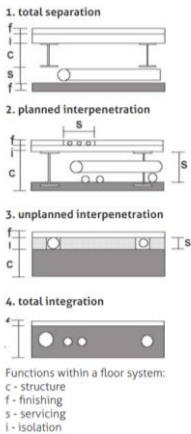
A building component can be taken from a building, if it is defined as an independent part of the building's structure. The first step that must be made is to subdivide the building into different sections that have different performances and different life cycles.

Four main building functions are: supporting, enclosing, servicing, and partitioning. Each of these can further be subdivided into subsections (subsystems) such as: foundation, frame, floor, façade, roof, inner walls, ventilation, heating system, water system, electrical system, etc.

Each of these functions has different behaviors, and provides different effects such as: heating, reflecting, distributing, ventilating, lighting, or deals with effects such as tension, compression, etc. Therefore, 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.



Functional autonomy Incorporation provides a partial dependency between independent functions 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.



Assessment functional autonomy	
1. total separation (modular zoning)	1,0
2. planned interpenetration for different solutions	0,8
3. planned interpenetration for one solution	0,4
4. unplanned interpenetration	0,2
5. total integration	0,1

Incorporation of independent functions, result in the following strategies: Total integration, planned interpenetration, unplanned interpenetration, total separation. For example, integration between structure and services:

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.

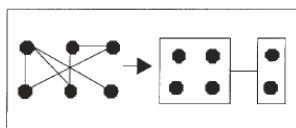
Strategy 3:

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

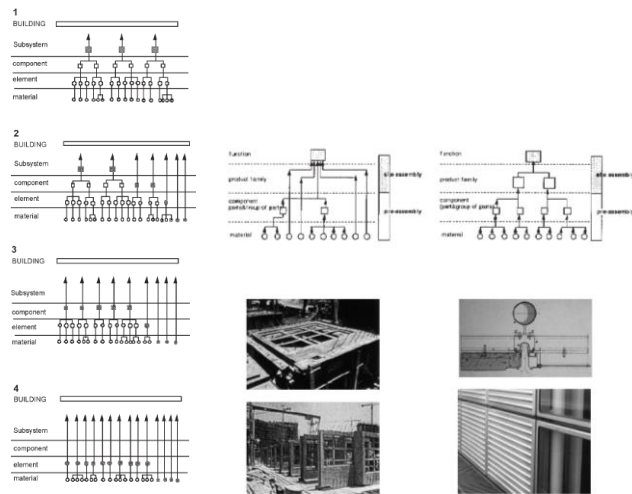
Strategy 4:

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.

2. SYSTEMATISATION

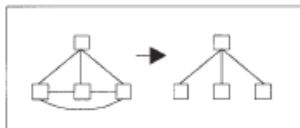


Building system is the most representative collection of parts that represent major building function. The system is the highest material level of technical composition and contains a number sub-levels, such as: sub-systems / components, elements, and materials. The number of disassembly options can 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/reconfiguration. Secondly disassembly in factory, where lower levels subassemblies, such as sub-components and elements, are disassembled and repaired for reuse/reconfiguration/recycling.



Four types of building configuration distinguished by the number of on-site assembly/disassembly operations.

3 RELATIONAL PATTERN



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

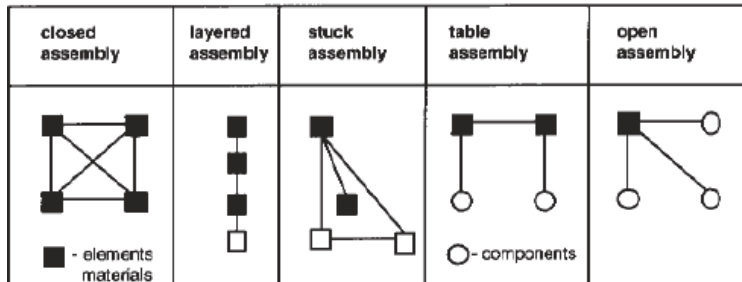
PATTERN TYPE

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 structures, is the number of relations. Distinction can be made between six relational patterns that result in six types of assemblies:

1. closed assembly , 2. layered assembly, 3. stuck assembly, 4. table assembly
5. open assembly



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).

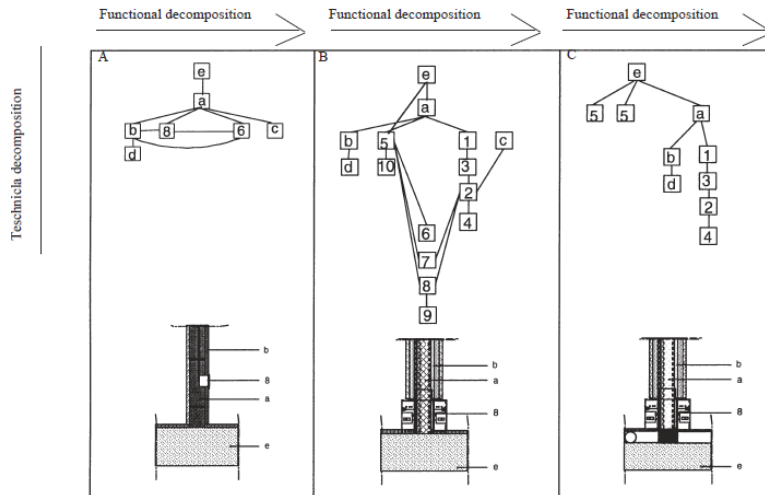
POSITION OF RELATIONS

Relations within sub-assembly versus relations between sub-assemblies

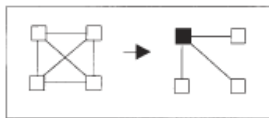
Relational diagram can be interpreted as represent relations between different family/functional groups (represented horizontally) , while each column represents technical decomposition within one family group.(see figure bellow)

The main rule is that sub-systems can only have relations with the base element of the structure. In this way, components/elements that belong to subsystems, can easily be replaced.

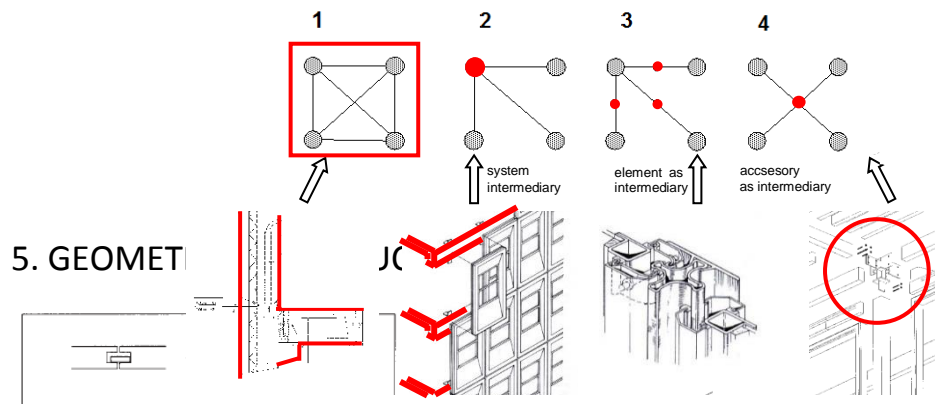
Vertical relations represent relations within one functional group, while horizontal relations represent relations between different functional groups. Ideally, different functional groups should not be directly related. This makes replicability and modifications of different requirements more feasible.



4. BASE ELEMENT

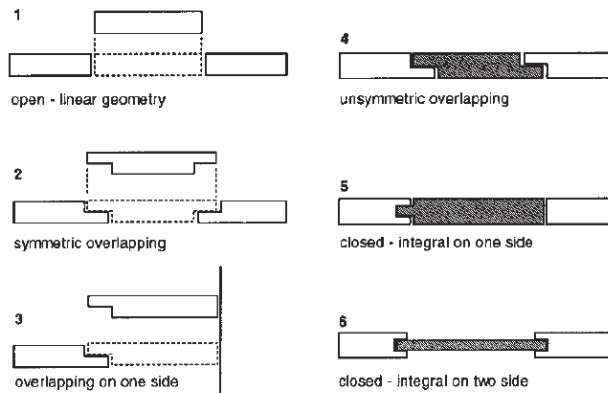


A building product(system/component/element) is a carrier of specific building's functions. Each assembled product represents a cluster of elements that are carriers of sub-functions. To provide independence of elements within two clusters, each cluster should define its base element, which integrates 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 (see figure below)

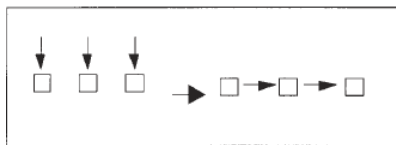


5. GEOMET

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 geometry for disassembly of components. Major two distinctions can be made between open and interpenetrating geometry. 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.



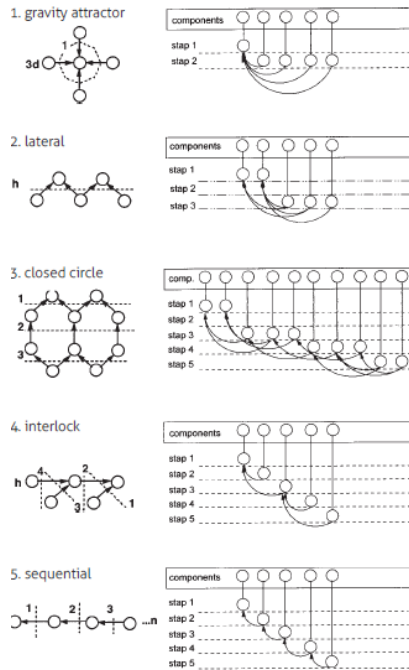
6. ASSEMBLY SEQUENCES



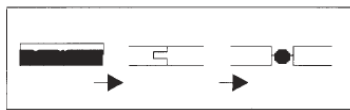
Life cycle of assembled materials, type of materials, geometry of product edge, and type of connections influence assembly/disassembly sequences.

Sequences in assembly represent complexity of the structure and dependencies between building elements. The way we assemble a building sets the mirror image of the building during its transformational and disassembly phase. Two major 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/ 2 gravity attractor / parallel , 3. closed circle ; 4. interlock , 5. Sequential (see figure bellow)



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 (integral), 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. 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: internal, 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. Dismantling 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.

Filed connections

These are connections between two components that are filled with chemical material. Assembly of such components is labour 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.

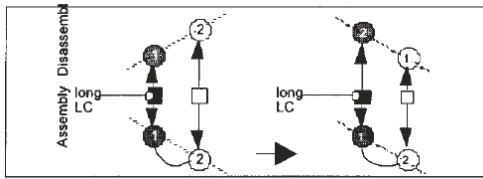
Disassembly characteristics of a connection depend on:

- the number of connection devices,
- type of the material used in connection, and
- the form of a component's edge.

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

fixed		type of connection	graphic representation		dependence in assembly
		I Direct chemical connection two elements are permanently fixed (no reuse, no recycling)			$m1 \rightarrow el2$
		II direct connection: between two pre-made components: two elements are dependent in assembly/ disassembly (no component reuse)			$el1 \rightarrow el2$
		III indirect connection with third chemical material two elements are connected permanently with third material (no reuse, no recycling)			$el1 \xrightarrow{m1} el2$
		IV direct connections with additional fixing devices two elements are connected with accessory which can be replaced. If one element has to be removed than whole connection needs to be dismantled			$e1 \xrightarrow{c1} e2$
		V indirect connection via dependent third component two elements/components are separated with third element/component, but they have dependence in assembly (reuse is restricted)			$el1 \rightarrow c1 \rightarrow el2$
		VI indirect connection via independent third component there is dependence in assembly/disassembly but all elements could be reused or recycled			$el1 \rightarrow c1 \rightarrow el2$ $el1 \rightarrow c2 \rightarrow el2$
		VII indirect with additional fixing device with change of one element another stays untouched all elements could be reused or recycled			$e3 \rightarrow c \rightarrow e1$ $e3 \rightarrow c \rightarrow e2$

8 LIFE CYCLE COORDINATION OF MATERIALS



One aspect of life cycle coordination in assembly deals with integration of materials with respect to their life cycle. 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 often assembled first.

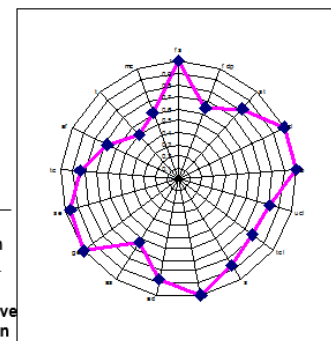
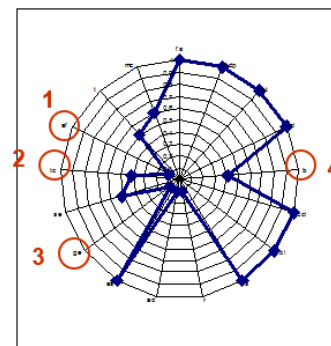
Elements, which have long life cycle and greatest dependencies in assembly, should be assembled first and disassembled last. Elements, which have short life cycle, should be assembled last and disassembled first. Two life cycle co-ordinations are significant for transformable structures:

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

OVERVIEW OF REVERSIBILITY

When analyzing seven 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.

nr.	Design for Disassembly 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)



	1	2	3 & 4	
Sequential assembly				existing solution
Parallel assembly				Alternative solution

In order to inform designers on the criteria and the design process which can improve design solutions for reversible building (products) structure, a specification of the design criteria has been made for major design phases: preliminary design, definitive design and technical design (preparation for construction). The criteria address three levels of dependencies between product structures: functional, technical and physical. During the preliminary design phase, the focus of design lays on the functionality of the design object. In terms of reversibility, functional decomposition is an important design criteria. 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, and which are not, will determine the product's reconfiguration options.

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 dependencies between elements and components also play a role in reversible solutions. Finally, during the technical design for the execution of construction, the independence of assembly sequences, the geometry of product edge and the typology of connections will ultimately determine the level of damage of recovered building products and materials.

If a designer places more focus on transformation than functional decomposition, technical composition would be a greater priority. If a designer is focused more on high value recovery and reuse of single parts, physical decomposition will be of greater interest. However, ultimately, if a designer is designing a reversible building, all three levels of decomposition of a building (functional, technical and physical) are of equal significance.

Design protocol for technical aspects of reversibility

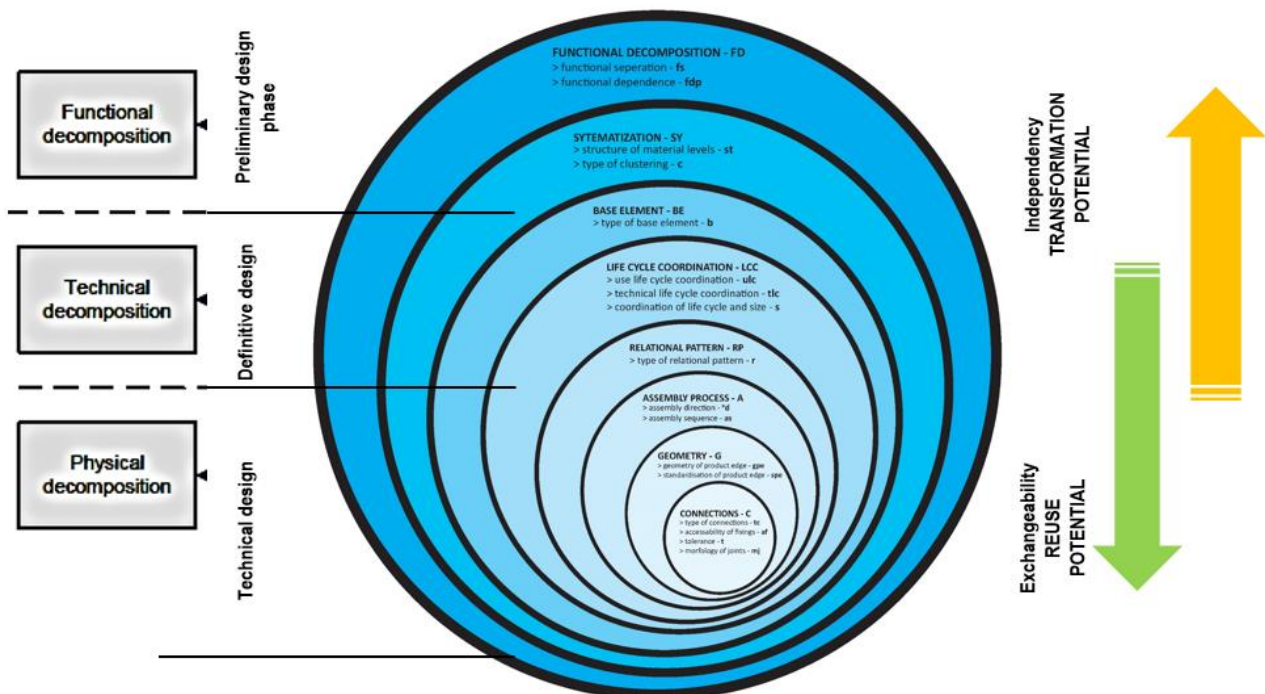


Figure : Reversible building protocol for technical aspects of reversibility.