DESIGN ASPECTS OF DECOMPOSABLE BUILDING STRUCTURES

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ABSTRACT

Technology innovations, population growth, evolving ecology problems, changing economies and life styles are imposing new requirements on a built environment. This influence considerably the way we ought to design and build in the future.

The most important issue regarding the building today is related to the increase of its environmental efficiency which can be achieved by creating the potentials for closed loop material cycling of building products. One of crucial problems of today's building construction is that buildings are made in such a way that many alterations lead to demolition of building parts or even whole structure. The main reason for this is the fact that different functions and materials comprising a building system are integrated in one closed and dependent structure which does not allow alterations. This is one of reasons for immense waste accumulation.
In order to improve environmental efficiency of the building we need to change our perception of the building's life cycle and its technical composition. This brings a focus on building assembly and combination of building materials and their functions at connections. Herewith deconstruction can be recognized as important element of sustainable construction. By adopting the concept of design for disassembly spatial systems of a building are become more amenable to modifications and change of use. At the same time the technical composition of a building become transformable what is precondition for reuse and recycling of building components.

The aim of this research is to specifying decomposition characteristics of building structures, which will determine the future recycle potentials of the building, its components and materials. This will be done by developing performance indicators of building structures that give a measure of their effect on deconstructability and reusability. Accordingly design guidelines could be developed which will steer the design so that decomposition of building and its components is possible.

Key words: deconstruction, flexibility, dynamic structures, sustainable

INTRODUCTION

The goal of sustainable construction is to build more efficiently and profitably after adopting responsibly to wide spread concerns about waste, pollution, nuisance, quality and users satisfactions [3].

However conventional design is concentrated on the classic building properties optimizing function, construction and costs in relation to the short-term performance. Such approach does not take into consideration aspects related to the future transformation of building structure, what has environmental and economic consequences.
An all embracing opinion is that a sustainable building is a building which:

(a) consumes a minimal amount of energy over its life span,
(b) makes en efficient use of environmentally friendly, renewable or low embodied energy materials,
(c) generates a minimum amount of waste and pollution throughout its whole life span
(d) utilizes local recyclable and reusable materials avoiding use of composites since they rarely can be recycled
(e) meets its users needs now and in a future. [3]

In the wide area of researches that have been done in the field of sustainable building great attention has been given to design of energy efficient buildings and use of environmentally friendly materials. Accordingly the tools are being developed to assess the environmental impact of building materials as well as to measure energy use during the operation phase of the building. However the design of sustainable building deals, on one hand with optimization of appropriate materials and energy use and, on the other hand, with optimization of appropriate construction methods and connections between building components. This means that the construction features influence the environmental impact of the building as well. The consideration of this aspect is not satisfactory and should get grater attention. More over the construction industry is mainly focused on the improvement of assembly techniques but very little to ease disassembly process. Therefore most of transformations within the building end up with demolition and waste disposal.
For that reason the design of sustainable building runs the danger of being carried out on ad-hoc bases without disintegration aspects of the building structure being an integral part of the design process. That means that we must consider how we can access and replace parts of existing building systems and components, and accordingly how we can design and integrate building systems and components in order to be able to replace them later on.
Ultimately this means that the buildings should be designed according to the criteria that will provide easy changes relaying strongly on the manner in which the building is assembled. This articulates the concern for design of building configuration. Configuration design deals with arrangement of building elements and components by defining the relationships between them. Through such process the level of independence and exchangeability of building components (being the indicators of decomposability) can be defined.

BUILDING TRANSFORMATION

Every building represents integration of spatial, technical and material systems. Very often building structures have dependent relations between building materials, components, systems and space. They follow the pattern of *fixed* integration of materials into closed structural systems. Consequently such systems are integrated into *fixed* spatial systems of the building [5]. Taking into account such general dependency from material systems to spatial systems every change within the building can have consequences for the entire building structure. At the moment that changes and modifications of building structures are almost

everyday activity, such fixed structures are no option. Modern buildings are being visualised by their makers as static and permanent structures. But, in the longer time frame the building is constantly changing due to changing user demands and the degradation of more technology dependent components.
Rather than destroying structures and systems while adopting the building to fit new requirements, it should be possible to disassemble sections back into components and to reassemble them in the new combination. At the moment that the act of demolition is replaced with disassembly building components would get a chance to have multiple lives which would drastically extend their life cycle.
Therefore one of key issues of sustainability is development of the design strategy that will transform inflexible building structures into dynamic and flexible structures whose parts could be easily disassembled and later on reused or recycled.
This would drastically improve capacity of building structure to be transformed on all levels from building to the material level with minimal environmental stress.
Three dimensions of transformation namely structural, spatial and material transformations characterize such decomposable structures.

- *Spatial transformation* ensures continuity in the exploitation of the space through the spatial adaptability,

- S*tructural transformation* which provides continuity in the exploitation of building and its components through replaceability, reuse and recover of building components

- *Element and material transformation* providing continuity in the exploitation of the materials through recycling of building materials.

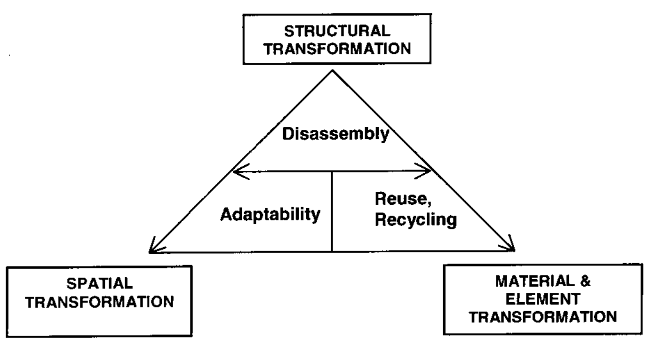

Figure 1: disassembly - the key for building transformation [5]

The key component of such three-dimensional transformation capacity of building is structural transformation with associated disassembly. Without disassembly spatial systems (whose life cycle very from 2-20 years [11] would not be easy transformable. On the other hand without disassembly the life cycle model of building materials (whose durability vary from 5-75 years) is linear and ends up with demolition and waste disposal.

INCREASE OF SUSTAINABILITY BY DESIGN FOR DISASSEMBLY

The demolition of building structures produces enormous amounts of materials that in most countries result in significant waste streams [9].
Generally problem is that the buildings and building products are not design for disassembly and repair. For that reason their life cycle is always presented as a linear system which represents one directional material flow from material extraction, manufacturing, transport, construction, operation, demolition and waste disposal. Such use/dispose scenarios are stimulated by the consumption related economy. Earth's resources are limited. But at the some time economic prosperity of modern society is based on consumption of earth's limited resources. With the explosion in world population and the increasing rate of consumption, it will be increasingly difficult to sustain the quality of life on earth if serious efforts are not made now to conserve and effectively use earth's limited resources [2].
(UN 1987) Agenda 21 from the UNCED conference in Rio 1992 states that cyclic processes must replace linear once to create sustainable development [1].

According to the EEA [7] Building industry in Europe produces 410 million tones per year (1995) with yearly increase of 9.7 million ton.
Recent studies [7] show that the largest quantities of waste are minerals originated from the structures. They also show that due to the contamination, a fairly large part of the recycled material is limited to low quality use or even landfill. This is mainly because present structures and components are not designed to be reused in new buildings since components can not be taken apart. Further more they are not designed to be recycled because they are often composed of hazardous materials.
Industrial ecology recognises the increase of the recycling rate as the most effective way to reduce the environmental impact. A major method to achieve higher rate of recycling is design for disassembly (figure2).
Looking at the last phase of the building it becomes very clear that if the act of demolition would be replaced by disassembly materials and components could be reused and finally recycled.
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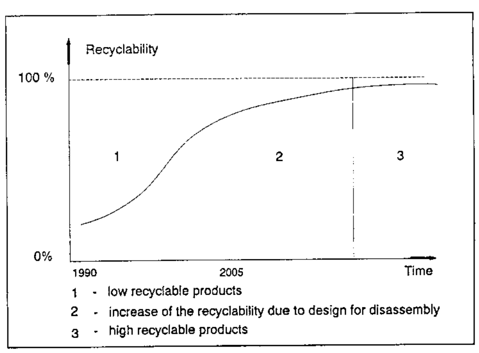


Figure2: increase of recyclability by design for disassembly

End of Life cycle scenarios

Recycling has different scenarios, which are often named as End of Life Cycle Scenarios. The environmentaly beneficial hierarchy of these scenarios which is widely accepted in product manufacturing industries can be presented as follow (Table 1):

Table 1: Hierarchy of End of Life Cycle Scenarios

		Recycling levels
I	REUSE,	Level 1
II	REMANUFACTURE,	
III	RECYCLING (up-cycling) & (down-cycling),	Level 2
IV	BURN,	Level 3
V	LANDFILL	Level 4

The aim of each of these strategies is to find a better way to make more efficient use of the limited earth's resources, minimize pollution and waste.

Reuse

This scenario is based on prolonging the life of the building or the building components by dismantling the component at the end of its functional life cycle and reusing it in a new combination. This is seen as the best environmental option because it uses minimum energy and material to close the loop of component or building life cycle.

Remanufacture

This strategy involves reconfiguration of existing component or system to restore its condition to "as good as new". This may involve reuse of existing components; replacement of some component parts and quality control to ensure that remanufactured product will meet new product tolerances and capabilities. [2] Good examples of successful remanufacture strategy are Kodak's single use camera, Xerox, Siemens computers etc. The same strategy could be applied for building systems or components.

Recycling

This recognized the fact that many of the earth's landfills are filling up at an alarming rate. Further more many of the "deposits" are hazardous and unsafe. It is therefore important to design the building components with ease of recycling so that a new product can be made from recycled material (up-cycling) or disposed so that final waste generation is disposed safly (down cycling).

Although present research and development R&D is directed mainly to energy conservation and waste management the greater effect in long term will be from reuse of the built environment on all levels from the building to the materials.

The key technical factor here is the planned ability of the building to be dismantled into its components parts. This brings a focus to the assembly and jointing methods. Easy dismantling of all components will allow a longer service life of the whole building by facilitating easily repeated repair, replacement and modification. The design of the building connections prevents us acting within level one and two (table 1). Having in mind existing building methods we are restricted to recycling level three and four (table 1).

MATERIAL LEVELS WITHIN THE BUILDING STRUCTURE

The perception of a building as one compact static product is misleading.
Duffy wrote in his book " Measuring building performance" "..our basic argument is that there is not such a thing as a building….a building properly conceived is several layers of longevity of built components [4].

The building structure is defined as a hierarchical arrangement of elements and relations the building consist of. It represents the way parts are arranged in the group of parts (components) and the way group of parts are arranged in the whole building [10].
Traditional buildings were characterised by complex relational diagrams representing maximal integration of all building elements into one dependent structure. (Figure 3 left)
The evolution of building structure represents the transformation from the complex relational diagram to the simplified relational diagram. The first step towards simplification of relational diagrams has to do with clustering a group of parts into independent subassemblies, which will act, independently in production and assembly/disassembly phase. (Figure 3 right)

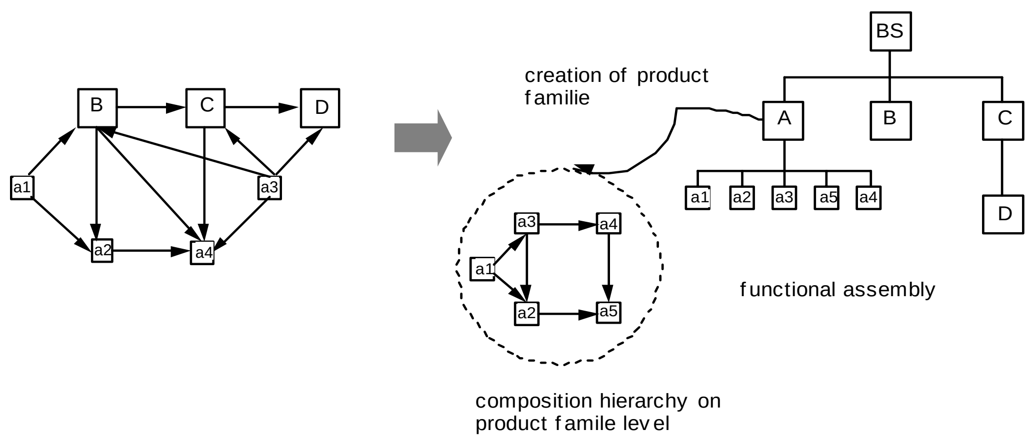


Figure3: Towards simplified relational diagrams between building parts

One subassembly is a group of parts with a property that the parts in subassembly can be assembled independently of other parts of the building. These subassemblies exist on different levels within the building.
Elements are seen as the basic parts that form the lowest level of building subassembly which is called component level in this research. In the same way that elements could be connected to form low-level sub-assembly (*component),* so this low-level assembly can be connected to form higher-level assembly (*system*).
The requirements for easy assembly and disassembly results in the selection of construction strategies that utilize prefabricated modular, dry jointed systems.

Unlike the traditional building structure which is seen as a hierarchy of elements the decomposable building structure should be seen as a hierarchy of subassemblies. It should be described at any level of abstraction: at the highest level *(building level)* as an overall assembly of systems, at intermediate level *(system level)* as composition of components and at the lowest level *(component level)* as assembly of elements/materials. (figure 4)

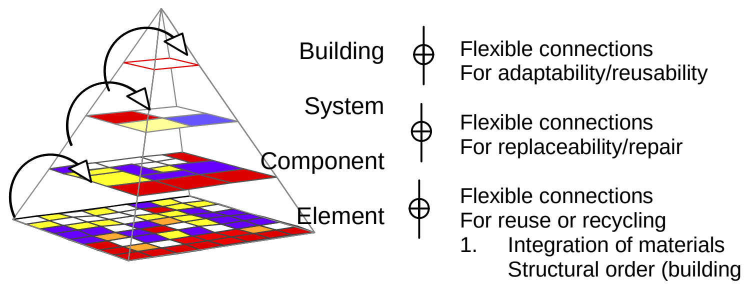


Figure 4: hierarchy of material levels

Having in mind that the structure represents functional assembly, hierarchical levels of building composition can be defined as follow:

- Building level represents the composition of systems which are carriers of main building functions (load-bearing, enclosure, partitioning, servicing)
- System level represents the composition of components which are carriers of the system functions (bearing, finishing, insulation, reflecting, distributing etc)
- Component level represents the layered or frame assembly of component functions which are allocated through the elements and materials at the lowest level of building assembly.

Bearing this in mind it is important to note that every material level within the building has to do with integration of functional and technical life cycle of building materials. This life cycle co-ordination is essential for design for disassembly. For example decomposition of one dwelling into independent levels is a top-down process. The specification of independent levels is related to desired flexibility scenario that will indicate the hierarchy of fixed and changeable components.(figure 5)
Thus the matrix of functional and technical life cycle coordination which is based on developed scenarios for future use of building and its materials is the starting point for design for disassembly.

The example in figure 5 left represents one hierarchical organization of building components. Specified hierarchy was based on the assumption that the dwelling should have maximal lay out flexibility. This includes replace-ability of the kitchen and wet units and separation walls. Herewith four independent time levels were recognized which indicated the hierarchy of building components.
Accordingly flexible technical systems were developed where water, electrical installations and separation walls were given shorter use life cycle than the rest of the building (figure 5 right). Further more the physical separation between fast cycling and slow cycling components was optimized through their interfaces.

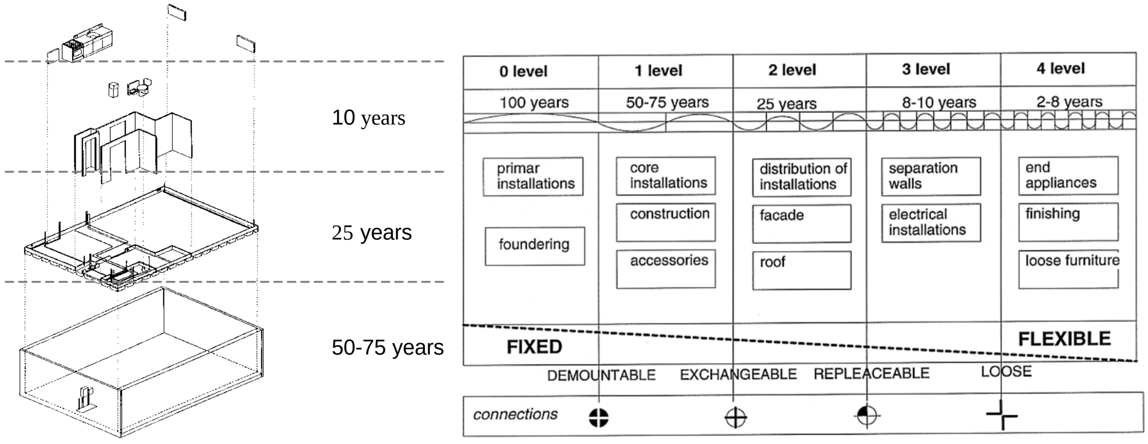


Figure 5:One proposal for systematization of building systems and their interfaces according to the different life cycles

The table on the right (figure 5) gives an overview of the use sensitive components within above defined flexibility scenario. The coordination between technical and use life cycle of building components is discussed further in the section 8.

Building Decomposition is the Sum of Decomposition Indicators on all Material Levels

A decomposable (constructed) building does not necessarily exhibit one structure but hides in its structure of components, and systems several different structuring principles that fit the building for construction, service and deconstruction.
Therefore the subassemblies of the building, their internal composition and the way in which they are built together determine the behaviour or function of the total building and its structure. Having that in mind it is impossible to speak of unstructured building, but we can speak of weakly structured buildings which we may reason from the properties “difficult to assemble”, “difficult to repair”, “difficult to change” or “difficult to disassemble”. The fact that different structures are superimposed in the final building makes the design integration and co-ordination complex and raises a need for design support tools.

A decision to create a cluster of parts is of essential importance in the design for disassembly. The more building parts are integrated into one component the less physical connections are needed on the site. In this why disassembly process can be accomplished in stages (on the site , in the working place, in the factory). Such strategy would be the first step towards greater control of efficiency of materials use.

The way we assemble the building reflects its disassembly process. Therefore the design decisions regarding the assembly, which are made, at the beginning of the design process can have consequences for the entire service life of the building and its materials.
For example one façade system can be structured following the pattern of functional decomposition (closing, finishing, isolation, water protecting ,bearing) and allocation of these functions through the independent elements which are arranged into components. This means that the components which have different functions could be independently replaced

at the end of their technical or functional life cycle. This is the characteristic of open façade system.
(figure 6 right) On the other hand the closed façade system integrates most of these functions into one composite component. (figure 6 left)

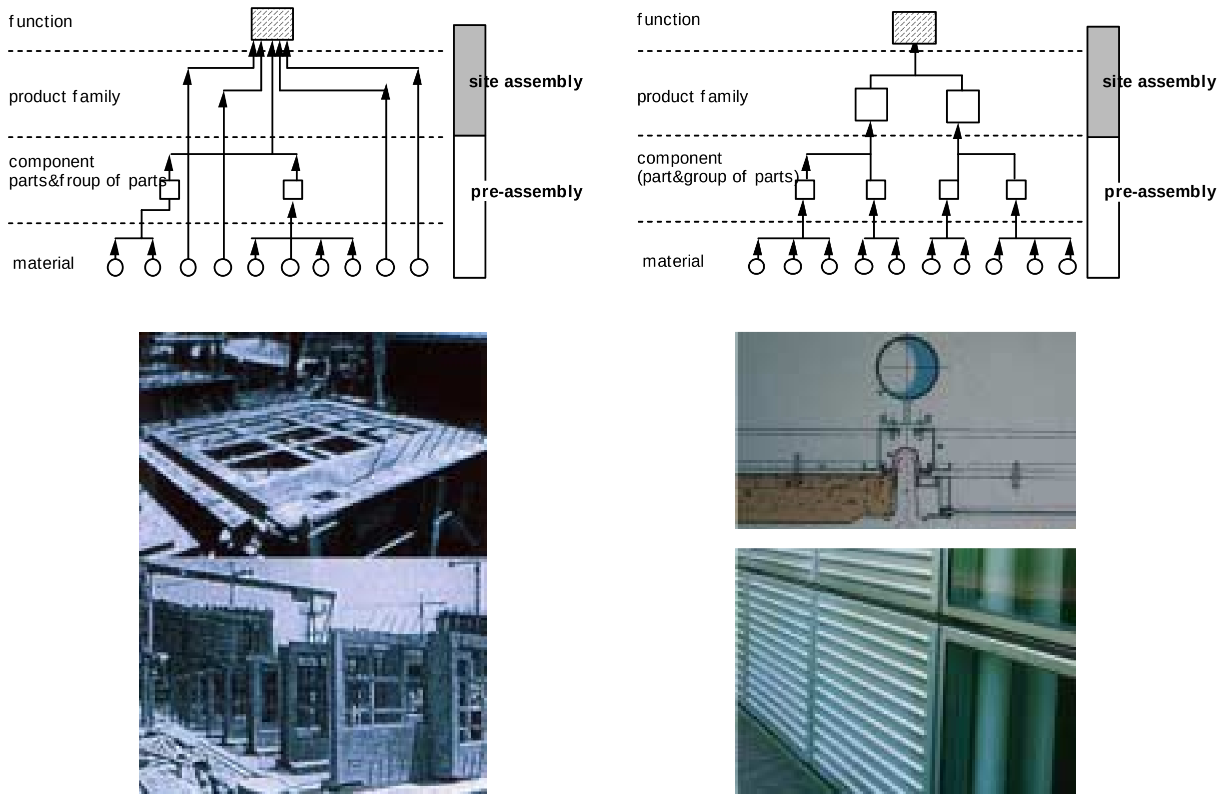


Figure 6: left closed system configuration, right open system configuration

The main disadvantage of such product structuring is in lack of transformation capacity of the systems. The second disadvantage can be recognised at the end of its service life, when the only possible scenario is demolition and waste disposal.

Having in mind that the building is the sum of structures, which are captured in a form of building, systems and components it is clear that total decomposition is related to the sum of disassembly properties on each of these levels of building integration. Thus total disassembly D(total) is sum of the decomposition on the building, system and component level (Dbl+Dsl+Dcl). Aspects, which can help to quantify “D”, will be discussed in the section 6 and 7.

$$D(total) = Dbl + Dsl + Dcl$$

Generally, it is possible to make distinction between fixed, partly decomposable and completely decomposable structures. The main difference is in the level of functional, technical and physical decomposition on each level of the building structure. For example one building function can be allocated through one independent building system. On the

other hand the internal composition within the system, just as the physical relations between the components of the system could stop further disassembly. One example is composite façade panel, which can be dismantled from the main structure, but the further decomposition on system and component level is not possible. In this case the total decomposition is:
D(total)= Dbl+ 0+ 0

CONFIGURATION DESIGN -THE KEY FOR DECONSTRUCTION

The current approach to designing a building and its structure is focused on the optimization of the building method to the cost, time and short-term use requirements. Sustainable development however raises a strong need for integrated life-cycle design, where all solutions are optimized and specified for the entire design service life of the building and its components. Such approach requires the development of different end of life scenarios for the building and its materials to which building methods would be optimized.

The end of life scenarios that are possible for the product will be determined by the physical characteristics of the product [4]. That is to say that the actual design of the building configuration will determine weather it is possible to achieve the environmentally preferable scenarios of maintenance and reuse, rater than just recycling and disposal.

Two main criteria for the decomposition of building configuration are *Independence* and *Exchangeability* of building components. In other words one building product can be dismantled if it is defined as an independent part of a building structure and if the interfaces with other parts are demountable.

Decompostruction characteristics of building structure could be specified by providing the performance indicator of building structures that give a measure of their effect on deconstruction. This can be achieved by analysing three main components of every structural configuration being: product type, relation’s type and connection type. (Figure 7) The design characteristics of these three components will determine weather the two main criteria for deconstruction: independence and exchangeability are provided.

The domains of deconstruction being structuring, product and connection domains (figure 7) can be distinguished but not separated from each other since they have mutual dependence in decision-making process. If one of the domains are not optimised for disassembly than the whole structure on specific level is not decomposable. For example if structuring and connection domains are optimised for disassembly the disassembly can be stopped by inappropriate geometry of product edge which is part of product domain. On the other hand we can have pre-made component with carefully specified aspects in the product domain but if the connections with other components are not designed for disassembly than the disassembly of the whole component will again not be possible and so on.

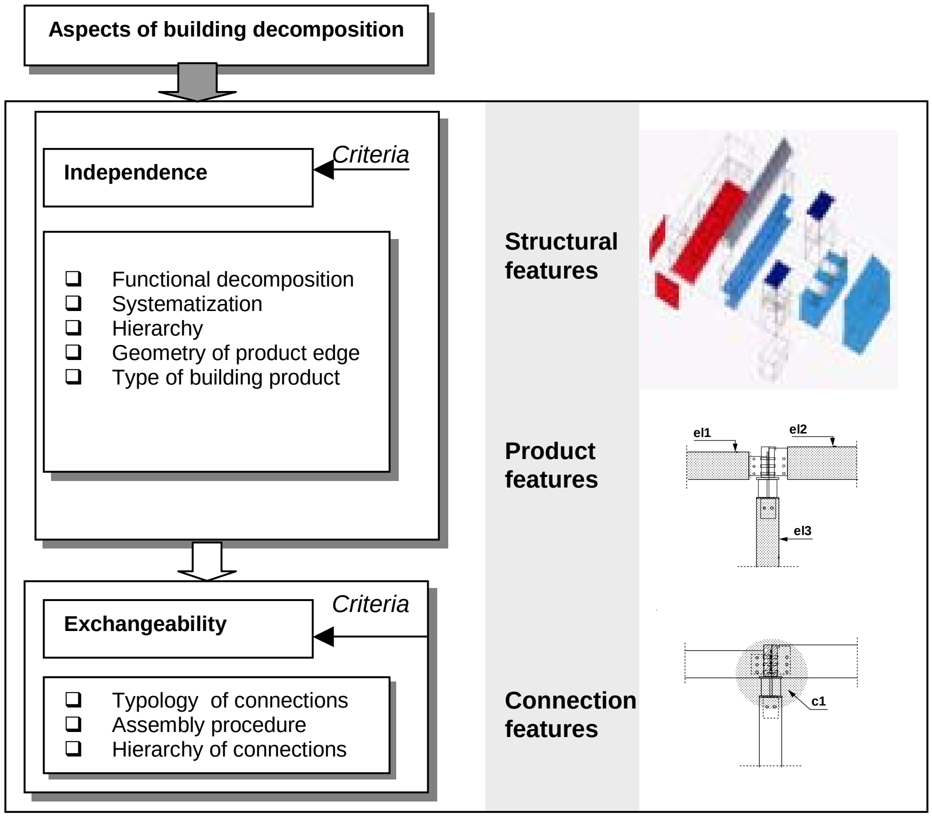


Figure 7: criteria for structural transformation

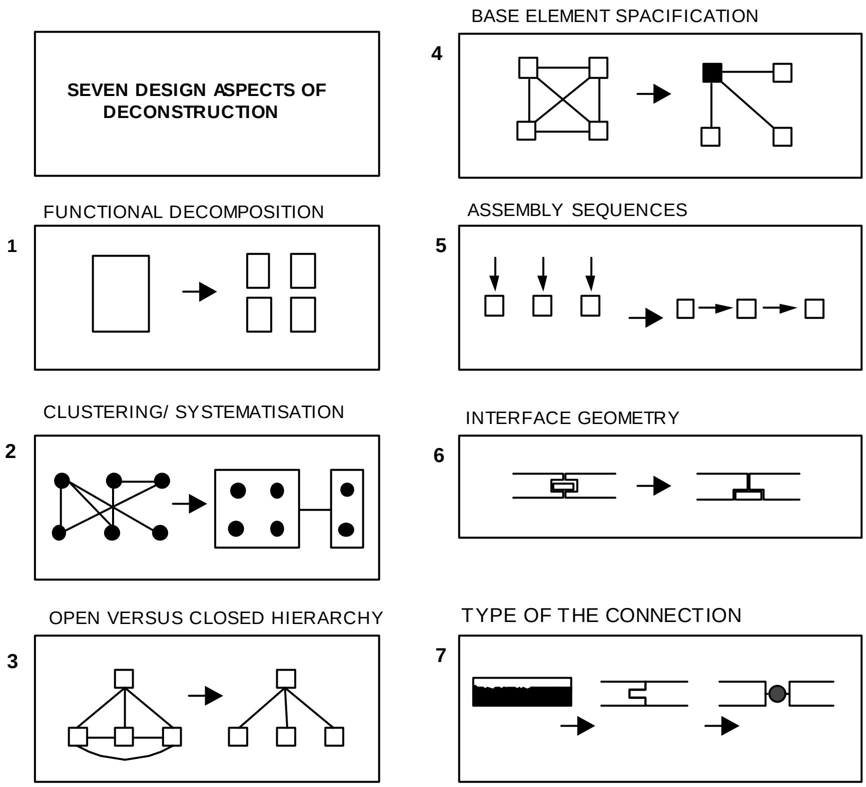
By analysing above specified aspect of structural transformation it would be possible to classify all building structures in rang from fixed, partly decomposable to totally decomposable.

Decomposable Aspects of Structural Configuration

Analysing the way building components are arranged and the relationships between them seven main design aspects of structural decomposition could be defined as listed in the table 2 below.

Specification of aspects in table 2 determines the performance characteristics of building structures and to what level they can fulfill the criteria of independence and exchangeability. Accordingly this will determine the disassembly characteristics of the structure itself.

Table 2: aspects of structural transformation



<u>Functional decomposition</u>

Decisions on whether the two or more functions are integrated into one building product or separate products are carriers of separate functions are made during structural composition design. The design for disassembly is in favour of total separation between different functions on all levels of the building's integration.

Four main building functions are supporting, enclosing, servicing and partitioning. Each of them has different behaviors and provide different effects such as heating, reflecting, distributing, ventilating, lighting or are dealing with effects such as tension , compression etc. Therefore the integration of two or more functions into one component can freeze their separation which may be necessary in order to answer new requirements.

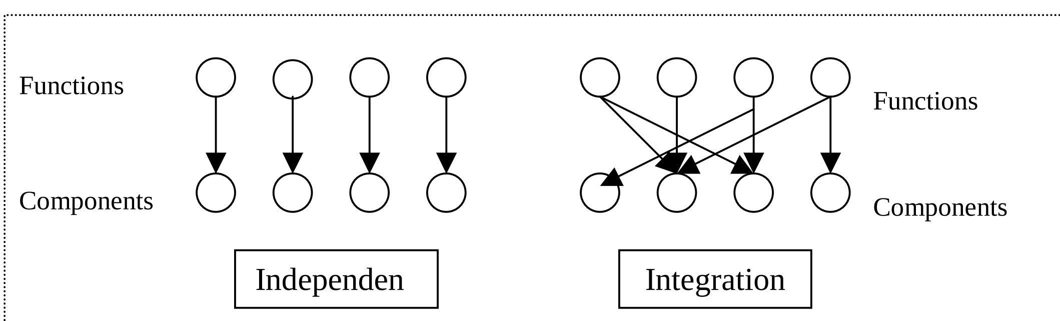


Figure 8: independence versus integration

Traditionally external walls, because of their composite and heavy structure, were seen as static and fixed parts of the building which are not supposed to be removed or transformed. Today such wall gained dynamic aspect since it has to enclose different activities, which are being changed quite frequently. Therefore there is immerging need to dismantle all functions which were kept within composite wall structure and allocate them thorough independent components so that the change or substitution of one function does not influence the integrity of others.

Clustering /systematisation

Traditionally all building elements were closely related to each other (with no respect to different functions and different Life cycles they had). In such environment the substitution of one element would have considerable consequences on all related parts at connections. One building component can be taken out from the building if it is defined as an independent part of the building structure. The first step that has to be made in that respect is to subdivide the building into different sections, which have different performances and different life cycles.
A subsystem is a cluster representing building elements which act as one independent building section in production and assembly-disassembly. The structuring principle for a subsystem aims amongst others at creating modular designs and standardization of elements on a sub-assembly level and on a component level. In that respect the development towards systematization and modulation of building parts into a subsystems presents the way to achieve more effective buildings with controlled use of row materials and less man power. The design team defines subassemblies based on required performance, production flexibility, system design and geometrical or mechanical criteria's.

Towards open hierarchy
When specifying the relations between subsystems for disassembly the hierarchy within the structure plays an important roll.
The hierarchy within the structure defines the order, which presents the path of the load through the building. This means that the hierarchy implies dependency, which is based on assembly. The load can be transferred through the building directly from one element to another.

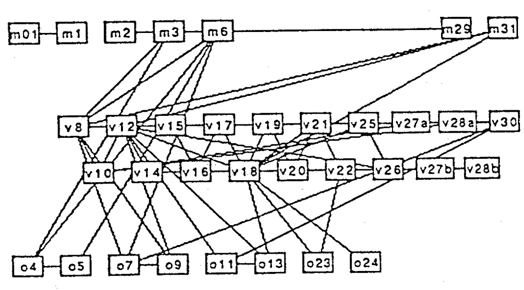


Figure 9a: close hierarchy (diagram of dependent relations within traditional building structure [12]
In such a way all elements become dependent from each other (figure 9a). The independence within a structure can be achieved by introducing a third part, which will take over the load bearing function.

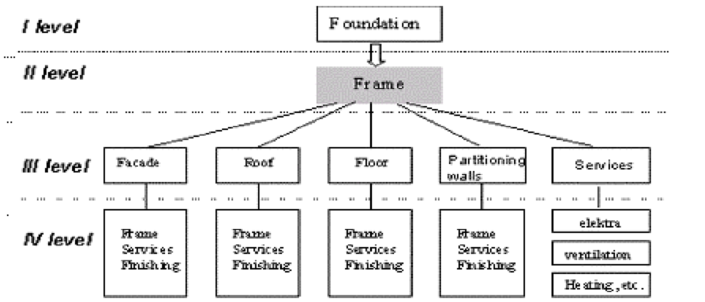


Figure 9b: Open hierarchy (principle diagram of dependent relations within decomposable building structure)

Generally if the traditional building structure = ∑ elements + ∑ relations, than the transformable building structure = ∑ clustered elements + ∑ coordinated interfaces.
Within open hierarchy building parts are kept independent from each other by creating dependent relation only to one element within assembly which is called frame or base element in this research.
Open Hierarchy can be achieved by different approach to design of building configuration. The main principle of new design approach should be recognition and separation of different time and functional layers of the building structure. This means that the design process should start with decomposition of the building into independent modules and base frame, which will connect distinct modules into one stable configuration (figure 9 b).

<u>Choosing the base part of one assembly</u>

Building product is a carrier of specific function or sub-function. Each assembled product represents a cluster of elements, which are carriers of sub-functions. In order to provide independence of elements within one cluster from the elements within the building, each cluster should define its base element which will integrate all surrounding elements of that cluster. Such element would be sheared on two levels in a building and its function would be dual: (i) to connect elements within independent assembly, (ii) perform as intermediary with other clusters.

The figure 10 shows four principles of defining the façade (for example) and the roll that specification of the base element can have on decomposition of the façade element. The principle 1 in figure 10 is based on the assumption that the building parts are assembled on the site. In this principle the elements, which according to their functionality belong to the functional assembly of the façade (f1), have direct relations with other functional assembly (load-bearing construction) (f2). The column (a) has the function of the base element for all elements in assembly, and therefore has connections with them all.
In principle 2, two functions (f1,f2) are clustered into one component. The wooden frame (b) is the base element for the whole assembly and at the same time, has load-bearing function in the building. This makes the construction process simpler but the change of one façade panel would have consequences for the stability of total structure.

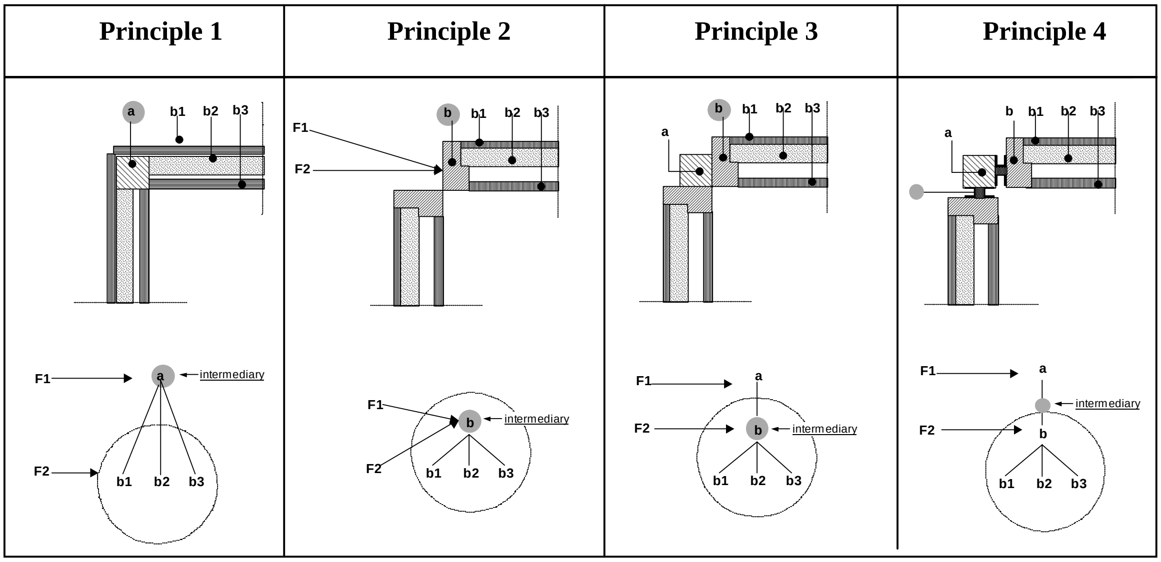


Figure 10: four principle solutions for the base part specification

Principle 3 shows the independent assembly of two independent functions (f1,f2). The elements that are assembled as façade (b,b1,b2,b3) are clustered into one component where the wooden frame (b) is chosen as the base element. Load-bearing function (a) is taken out and defined as independent assembly. In this case the load bearing elements act as the frame for whole building.
In the principle 4, a connection has function of intermediary between two independent assemblies. In this case replaceability of façade element (b,b1,b2,b3) would have no influence on the other assembly.

Product geometry

Disassembly sequences can be affected by changing the geometry of product edge. This aspect of the product feature is closely related to the interface design and specification of the connection type. Figure 11 left illustrates a standard detail which is often used in housing projects in the Netherlands. In this case disassembly of the window is not possible.
This is improved by change of the geometry of the connection figure 11right.

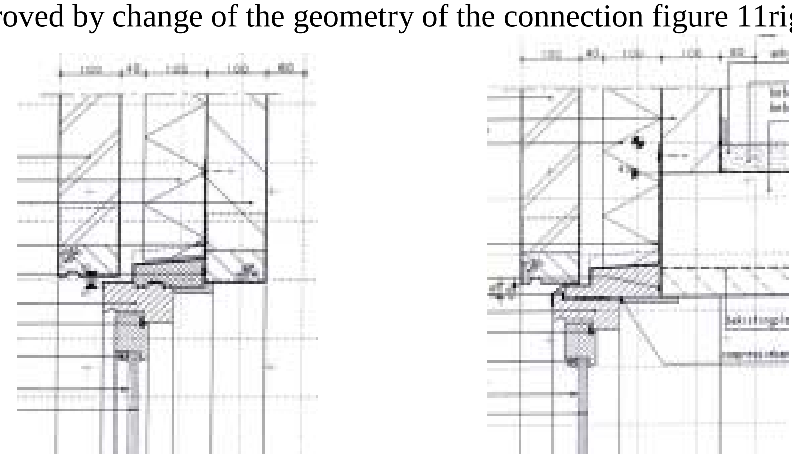


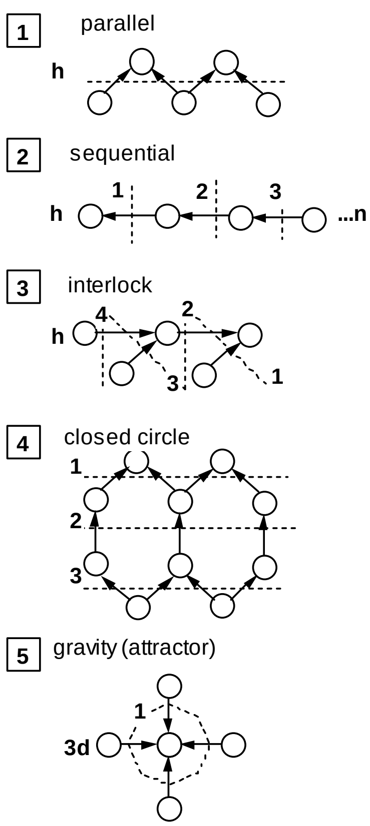
Figure 11: fixed and decomposable connection determined by the geometry

Assembly sequences gravity (attractor)

An assembly hierarchy shows the building breakdown from the assembly point of view. Two assembly sequences can be distinguished parallel sequence and sequential sequence.

Parallel assembly sequence can make the building process faster. While sequential assembly sequences create dependence between every assembled element and makes the substitution more complicated.

Five assembly relations could be defined based on above mentioned principles. The arrows in the figures 1 to 5 represent assembly sequences.



Parallel assembly. Disassembly will depend on the type of the connections between elements .

Sequential assembly. Each element in this assembly is fixed by a newly assembled element. In such a way a linear dependency is established which is proportional to the number of assembled components

Each element in this assembly has the same dependence as in number 2

This assembly scheme is a combination of 1 and 2. Transformational aspects of such a scheme will be related to the :

- Function of the elements which were assembled in the first three sequences
- Life cycle of elements which were assembled in the first three sequences
- Type of the connections

This is an assembly where one element has the function of base element for all other. The key transformational aspect here is the type of connection between the distinct elements

Building interfaces

Design of building connection is the last aspect of design for disassembly. Interface defines the degree of freedom between components (figure 12), through design of product edge and specification of connection type.

In general it is possible to define three main types of connections such as direct (integral), indirect (accessory)[8] and filled.

Integral connections are the connections in which the geometry of component edges forms a complete connection. Two basic integral connection types could be distinguished (i) overlapped and (ii) interlocked. *Overlapped* (figure 12, principle II) connections are often used as connections between vertical external façade components or between vertical and horizontal components. Their disassembly depends from the type of the material which is used in the connection, assembly sequences, hierarchical position of the components and their relations with other components. *Interlocked (*figure 12, principle IV) connection is internal connection in which the component edges are differently shaped. Further on the shape of the edges allows only for sequential assembly what complicates the disassembly.

Accessory connections are the connections in which additional part is used to form a connection. Herewith two types of connections could be distinguished internal and external. Internal type incorporates loose accessory which links components. The accessory is inserted into the components. The connection possesses the advantages of identical edge shapes to the components. The dismantling of such connection can be difficult because of the sequential assembly sequences (figure 12, principle V). The accessory external joint makes the dismantling easier with applied cover strips or with combination of frame and cover strip (figure 12, principle VI).

Filed connections

Those are connections between two components which are filed with chemical material on the site (figure 12, principle III). Assembly of such components on site is more labour intensive. Those could be welded connections between to metal plates, or beam and column, or it can be connection between two concrete floor panels or bricks etc. Disassembly of such connections is often impossible.

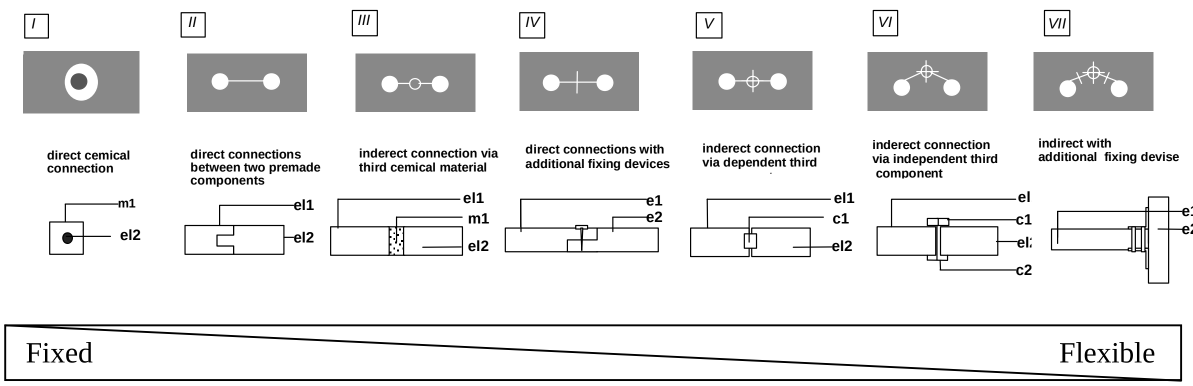


Figure 12: Seven principles of connections (m-material, c-connector, el-elements)

Four basic displacements that together make all transformations in the structure are elimination, addition, relocation and substitution. The structure of building or its parts can be transformed by the elimination of the element, it can be transformed by addition of the element, element can simply change its position in the building or element can be replaced with another one (substitution). The key technical problems here can be defined as capability of interface to provide decomposition, re-composition, incorporation and plugging in.

Two main criteria for design of decomposable connections therefore are:

1. all elements/components should be kept separated avoiding the penetration into another component or system
2. dry jointing techniques should replace chemical

These conditions should be applied accordingly on all levels in a building. In this way all systems brought together to form a building would be demountable, each component and element replaceable and all materials recyclable.

Furthermore disassembly characteristics of one connection depend on :
- The number of connection devices
- Type of the material used in connection
- Form of component edge

According to the above-specified characteristics connections could be grouped in hierarchical order from fixed to flexible. Figure 12 gives a hierarchical overview of the most common principle solution. The principle 7 (accessory connection) can provide technical solution for all four-transformation criteria. On the other hand the principle 1 represents the connection between two row materials which can only be demolished when changed. Further on principles range from direct integral connection (principle 2) whose decomposition is possible only if the whole structure is to be dismantled, principle 3 presenting connection between two elements with chemical connection and principle 4 where partial lap connection with additional fixing accessory creates precondition for decomposition and replace-ability. Finally principles 5, 6 and 7 represent dry connections where the position of accessory and its fixings determines their actual disassembly.

FROM FIXED TO DECOMPOSABLE STRUCTURES

By analysing the above-specified aspect of structural transformation it would be possible to classify all building structures in range of fixed, partly decomposable to totally decomposable structures.

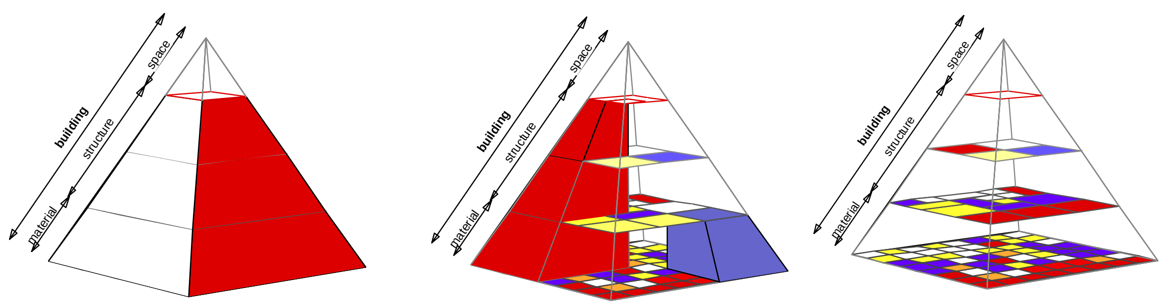


Figure 13: three principles of integration of material levels within the building [6]

Fixed structures
The main characteristic of *fixed* structures is maximal integration and dependence between building components caused by: (i)hierarchy of assembly which is not related to the component service life and expected time till obsolescence, (ii)application of sequential assembly sequences, (iii)design of integral joint type (components are shaped in such a way that bringing them together forms a joint), and (iv)use of chemical connections.

Partly decomposable structures are dependent on design strategies to which the hierarchy of fixed and flexible elements adjusted accordingly. Fixed elements are elements with high level of flexibility towards spatial and functional changes and high durability [6]. Flexible elements are elements which are frequently exposed to change.

The flexibility of such structures is restricted to the designed capacity of the fixed elements and the type of flexibility which was strategically chosen.

Totally decomposable structures can be totally dismantled at the end of their service life. That means that they could be relocated or that their parts could be reused in other combinations or be recycled. This group represents the structures which provide clear separation between all building components. They are composed of systems of modular parts that are easily transportable and usually dry assembled on site. Decomposable structures define a method of construction in which use is made of integrated structural, mechanical, electrical, envelop and partitioning systems in a way that will stimulate their independence and exchangeability. The most important aspect of such buildings is decoupling of levels that have different functional and life cycle expectancies.

The main characteristics of *decomposable* structures are (i)use of accessory joint types (they require additional third part to form the joint between two components), (ii)application of parallel instead of sequential assembly/disassembly, (iii)use of mechanical connections in place of chemical connections (iv) creation of open hierarchy of distinct modules. Such building configuration provide the precondition for independence and exchangeability of building components and accordingly their reuse or recycling.

Specification of Framework for the Diagrams of Deconstruction

Deconstruction characteristics of structural, product and connection features which are assessed through the aspects defined in this paper, can indicate the performance of the building structure in relation to its deconstruction. Through such assessment it would be possible to define the impact of different building configurations on the environment, and the potentials for building modifications. Structural, product and connection features of decomposition are mutually dependent. The disassembly of the structure is not feasible if one of these features is not optimised for disassembly. The decomposition on every level within the building can be presented through the dependent function of three variables (Sd-structural decomposition; Pd-product decomposition; Cd- Connection decomposition.
The dependence between different domains of decomposition could be presented through the 3D Diagrams. (figure 14)

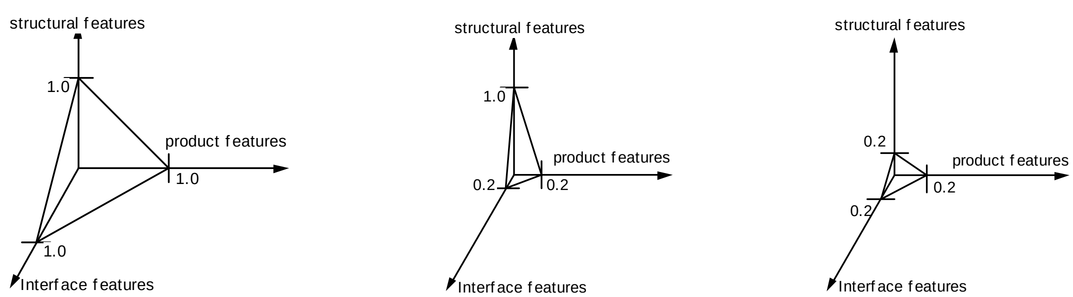


Figure 14: decomposable structure, partly decomposable structure, fixed structure

Diagram (figure 14 left) left represents a totally decomposable structure. This means that the structural decomposition features, product decomposition features and connection decomposition features are optimised for total disassembly. The diagram in the middle represent a structure which is partly decomposable like building which is constructed out of independent products but whose product features and interface features are not designed for disassembly (conventional system building). The diagram on the right is representation of fixed structure where structuring, product and interface features are not optimised for disassembly.

The success of decomposition can be measured on each level of building integration.

- Disassembly on building level deals with de-coupling of main building systems. The advantages are reuse of systems, spatial adaptability and functional adaptability of the building.
- Disassembly on system level comprises of separation between components, which are arranged into a system. The advantages are reuse of components, adaptability of system's functionality.
- Disassembly on component level deals with separation between elements and materials and its main advantage is in adaptability of the component's functionality, reuse of the elements and recycling of the materials

WHEN DECONSTRUCTION TAKES PLACE

The life cycle assessment of the deconstruction phase of the building can be measured by the energy which is being used for deconstruction and waste being created during deconstruction.

Buildings which can be easily transformed and whose components can be reused in another combination or recycled are more favorable than buildings whose only option during the deconstruction phase is demolition and waste disposal. Let us compare, for example, two brick facades. Brick elements put together in a traditional way create composite mass structure and brick elements put into a frame and fixed with bolts (R.Piano IRCAM building in Paris) compose a decomposable structure. Those are two extreme solutions showing that it is possible to design decomposable (sustainable) façades using traditional building materials such as brick, by inventing new ways of arranging bricks into a coherent configuration.

Of course the type of configuration that should be designed is related to the question of when the deconstruction will take place. Optimization of all aspects of structural transformation is related to the specification of two types of scenarios: use scenarios and end of life cycle scenarios (already discussed in previous text) of building products.

Buildings are constructed of elements and components which have different functional and technical life cycle. This can result in three lifecycle coordination scenarios.(figure 15)

1. functional durability of the component < the technical life cycle of the component.
   Such components should be reusable or recyclable
2. functional durability > technical life cycle of the components.
   Such components should be replaceable and recyclable.
3. functional durability = technical durability.

Such components should be recyclable

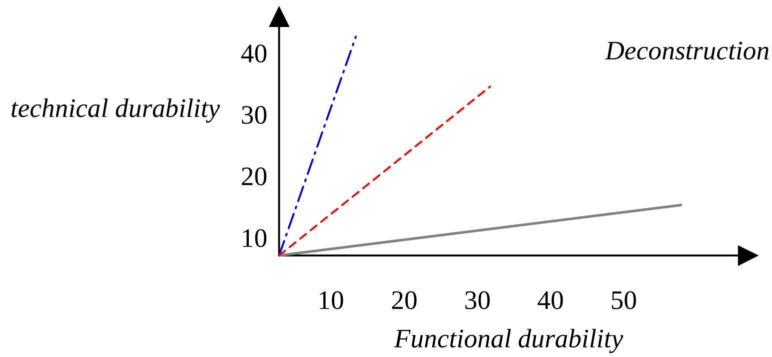


Figure 15: Technical and functional life cycle coordination

Our built environment is operating a great deal within scenario 1. Most of the social housing projects, offices and shopping molls could be located within this scenario. Those are buildings whose use sequences are relatively short compared to the technical durability of the whole building structure. Although the user requirements are often unpredictable it should be possible to define patterns of change within this group of buildings so that transformational aspects of their structures can be defined. Through building categorization it would be possible to define different morphological groups of structures and their transformational aspects.

Groups of buildings that belong to scenario 2 are monuments. For these types of buildings the maintenance of the building structures is the most important aspect.
Finally scenario 3 is to be found within a temporarily buildings. Such buildings have minimal number of time levels. The priority in configuring the structure for such buildings is in design for recycling.
Generally speaking deconstruction takes place between elements, component and systems which have different functional and technical life cycle. Theoretically speaking scenario 3 can operate within one time level. Scenario 2 can operate within 3 time levels. The number of these levels depends on the number of maintenance sensitive levels. In this case those are usually installations and finishing. Finally scenario 1 can be designed with up to X independent time levels. Their number depends on the scenarios for future use of the building and its components. The more time layers can be defined the more transformation sensitive the structure is and the longer life it can have.

CONCLUSIONS

Conventional building structures are not designed for change. For that reason every transformation within the building has to do with demolition of parts of a building or sometimes whole built structure. In order to increase the building's transformation capacity building construction has to focus on further systematization of building and development of innovative building methods that will provide flexible structures whose parts could be easily replaced and reused or recycled. In order to achieve this we need to change our perception of the building and its structural configuration. The assessment of structural configuration can help us to understand the nature of change and to define the transformational potentials of different structural morphologies.

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