Dynamic and Circular Buildings by High Transformation and Reuse Capacity

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Introduction

The exponential increase in population and contemporaneous increase in standard of living for many, will mean that the demand for essential goods & services (transportation, cars, planes, but also housing, materials, water, food) will increase by at least a factor 2 in the next few decades. If the need to support an additional 3 billion people and effect of increase per capita consumption is added it is clear that the linear material flow (from excavation to disposal) present in the existing industrial systems is not sustainable.

Massive processes of urbanization under way today are inevitably at the center of the environmental future. It is through buildings, cities and vast urban agglomerations that mankind is increasingly present at the planet through which it mediates its relationship to the various stocks and flows of environmental capital. The physical impact of the increasing building mass in industrial and developing parts of the world is undeniable. In Europe, the building industry accounts for 38 percent of the total waste production, 40 percent of the CO2 emissions and 50 percent of all natural resources are used within the building sector. (EIB 2015)

To answer above questions from building design point of view it is crucial to understand the capacities of buildings, to transform what is today a negative environmental impact of built environment to a positive one.

The key question is: how can we transform the linear thinking around the market economy, expressed in short product lifetimes and a society that deprives itself of natural resources, to more circular thinking whereby mass-production is linked to continuous replenishment of the natural resources, where concept of waste does not exist and whereby materials are circulating in continues loop forming a base for new circular economy? In other words it is crucial to understand the driving force behind the reversibility of processes that can insure circularity of building materials through their multiple applications.

Numerous researchers (Brand, Crowther, Vandenbroucke, Henrotay, Debacker, Hobbs, Beurskens, Durmisevic, Lichtenberg) as well as EU construction and demolition waste (CDW) reports, have one thing in common. They all indicate that there is a fundamental system's fault embodied in building design and construction, demonstrated through tons of CDW produced by continuous demolition activities when adopting, upgrading or replacing a building or part of the building.

This indicates that conventional outset from which buildings are designed and then constructed result into demolition as the predominant end of life option for buildings and their components. Considering the overwhelming negative impact based on this linear approach to use of buildings and resources within built environment, it has become evident that conventional design and construction methods are not sustainable on long run. The aim of EU Buildings as Material Banks project is to propose a design method that can eliminate this fault in the system, by proposing design tools and protocols that will reverse the processes of linear material flow into circular one as proposed in the theoretical diagrams below.

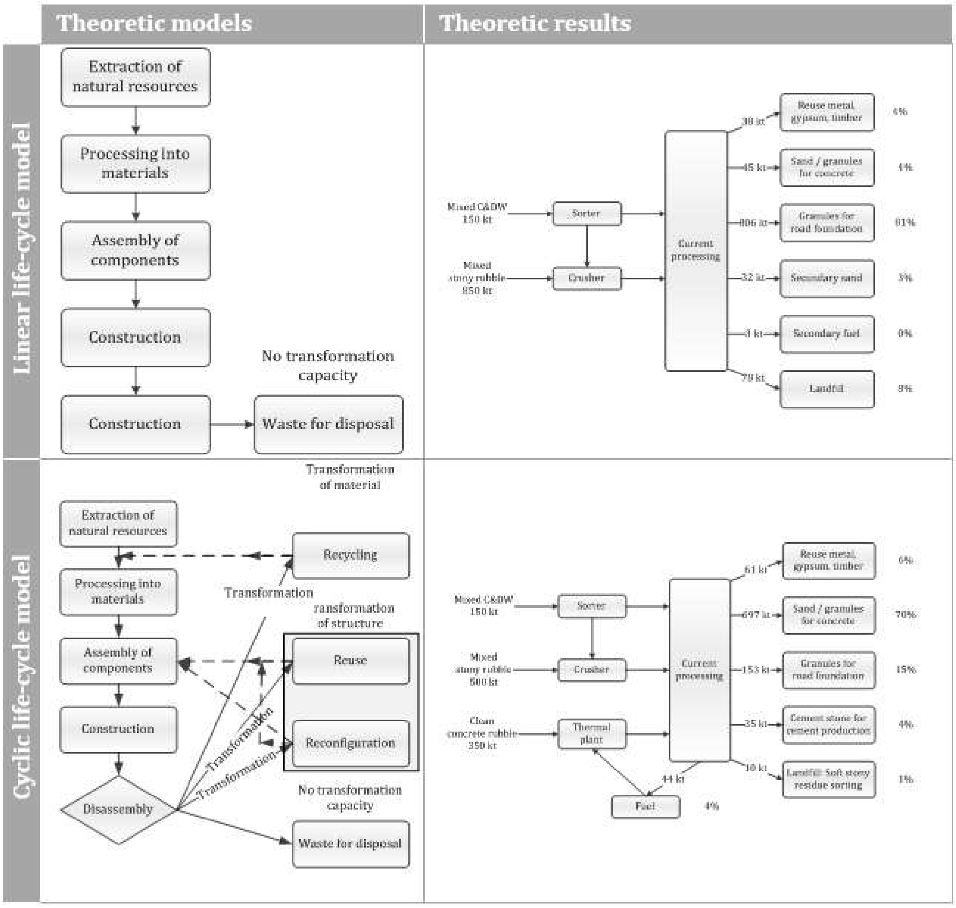

Figure 1: Linear vs cyclic waste material stream (Durmisevic 2006, Mulder 2008)

Existing building stock designed for demolition

Very often buildings are seen as finished and permanent structures. They are carefully designed around short-term predictions of building use. As a result those buildings have a long physical lifespan, but do not offer the flexibility to maximize their functional lifespan. For that reason, parts of such fixed building structures or whole buildings have to be broken down, in order to be changed, adapted, upgraded, or replaced (Durmisevic, 2006). Some buildings are demolished because their technical characteristics have deteriorated. Most buildings, however, are demolished because they do not satisfy the needs of their users. Conventionally, the technical and functional service life of a modern building is approximately 50-75 years. Yet, today buildings with an age of 20 years are demolished to give way to new construction. The average functional service life of a building is becoming shorter and this forces the return on investments to come more quickly (Durmisevic, 2006).

Representative example of this trend is the Fortist Bank Building in the center of Amsterdam which become subject to redevelopment and demolition 18 years after construction. As illustrated in the figure this has led to value degradation of building its components and materials to a low value material that can be used as a base for the road construction.

Figure 2: end of life value of typical office building in the Netherlands built 18 years ago.

Real-estate developers warn that existing building stock does not match with the continuous and ever increasing changes in market demand. This difference in supply and demand resulted in the huge vacancy. Only in the Netherlands, according to the national Planning Institute, the society has a burden of 8,5 million m2 of vacant office space without a use value (Planbureau voor de Leefomgeving 2013)

Ultimately modern buildings are designed and built based on conventional mono-functional and liner concept of use, consumption, demolition and waste disposal. They are not built for long life by concept of upgrading and adaptability to dynamic social, economic and climatic activities but for demolition. Their systems and materials are not designed and made as reusable for other useful applications, but as future waste. (Durmisevic 2015)

The data presented below indicates that the existing building stock in the Netherlands does not have the capacity to transform and adapt to changing market requirements. In the period 2010-2040, a predicted number of 600.000 dwellings will be replaced with new dwellings while in the same period, it is estimated that another 1 million new homes will be constructed. This means that about 38% of new construction is due to the replacement of demolished homes (EIB, 2015). Also, the fact that new office buildings are being built while the vacancy rate of offices is exceptionally high (10,7% of the total office stock of 69,5 million m²) indicates that current buildings do not reflect the wishes of end users (EIB, 2015). In addition, offices are not capable to change their use concept. 25% Percent of vacant offices has the capability to transform into dwellings. That gives a potential of 20.000 new homes in vacant offices (EIB, 2015). Major barriers faced when changing offices into apartments are related to the reduction of natural light due to the with and depth of the building block, fire escape routes and number of staircases needed for apartment buildings.

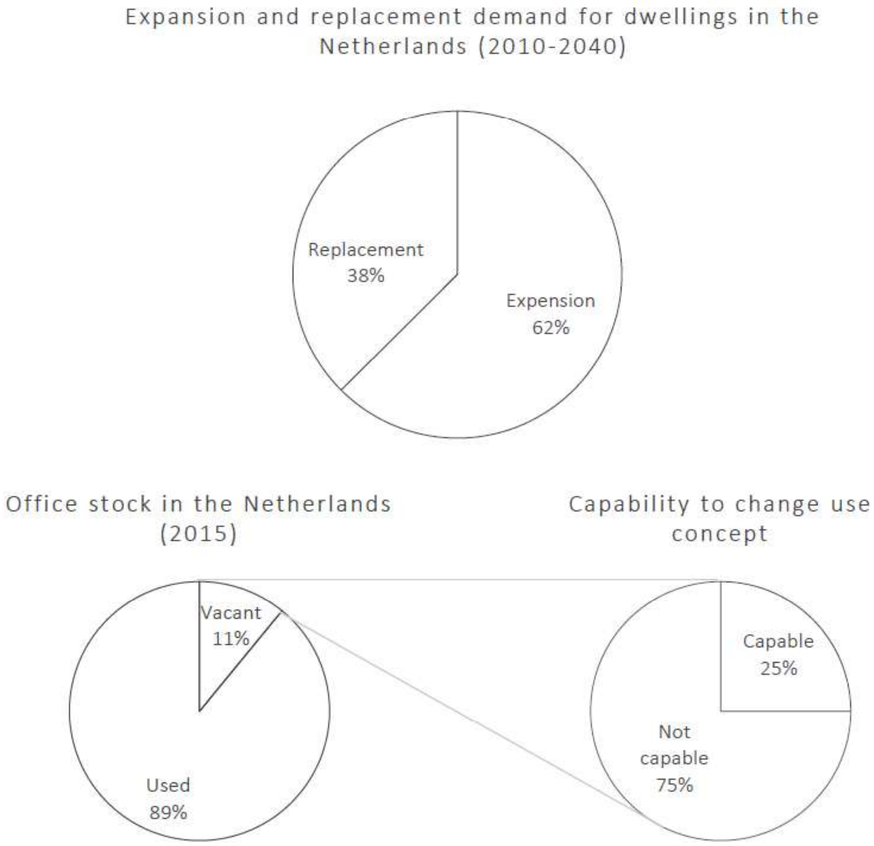

Figure 3: Buildings activities in the housing and office sector in the Netherlands (EIB 2015)

State of Building's reversibility

In an ideal case one can adopt as a goal that every molecule that enters a specific manufacturing process should leave as part of a saleable products; that the materials and components in every product should be used to create other useful products at the end of product life; (Greadel and Allenby), and that the main structure of every building can accommodate different use patterns during its total life. Unlike car and product design where concept of industrial ecology (closed life cycle of products) promoting Design for Disassembly approach has been investigated and applied in the past, this approach is revolutionary when it comes to the building design.

Demolition in general can be defined as the process whereby the building is broken up, with little or no attempt to recover any of the constituent parts for reuse. Most buildings (built particular after 1945) are designed for such end-of-life scenario. They are designed for assembly but not for disassembly and recovery of elements and components. Different functions and materials comprising a building system are integrated in one closed and dependent structure that does not allow alterations and disassembly. The inability to remove and exchange building systems and their components results not only in significant energy and material consumption and increased waste production, but also in the lack of spatial adaptability and technical serviceability of the building.

Such a static approach to building integration ignores the fact that building components and systems have different degrees of durability. While the structure of the building may have the service life of up to 75 years, the cladding of the building may only last 20 years. Similarly, services may only be adequate for 15 years, and the interior fit-out may be changed as frequently as every three years.

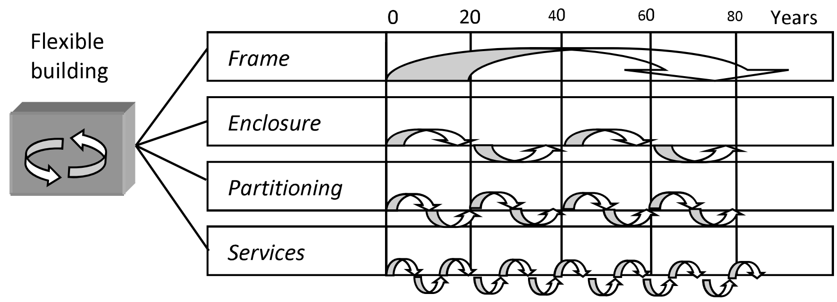

Figure 4: Different durability rates of building components (Durmisevic 2006)

Nevertheless, it is quite normal for parts with short durability to be fixed in permanently, preventing easy disassembly. This complicates replacement and repair schedules. Stewart Brand describes these variable decay rates as “shearing layers of change”, which create a constant temporal tension in buildings. Faster-cycling components such as space plan elements are in conflict with slower materials, such as structure, and site because of the permanent physical integration between different time levels. The first step towards managing the temporal tension in building is through decoupling of slow and fast time levels (Kibert 2000). A theory that Jhon Habraken introduced already in 1960 as an open building principle. Habraken defined two major time layers in the building as Support and Infill. Later on Duffy increased the number of layers to Shell, Services, Scenery, and Set and Brand in 1997 defined six changing layer (figure below).

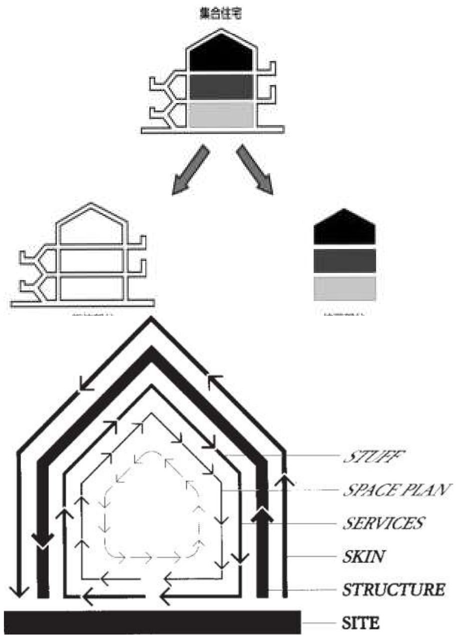

Figure 5: Changing functional levels within a building: left Habraken (1962) right Brand (1997)

However based on research from end of 1990’s and beginning 2000 it has been argued that in the case of transformable building structures it is not possible to fix a number of changing layers since they will depend on type of spatial flexibility or transformation required. Different transformation scenarios will require different number, arrangement and hierarchy of changing layers. (Durmisevic 2006)

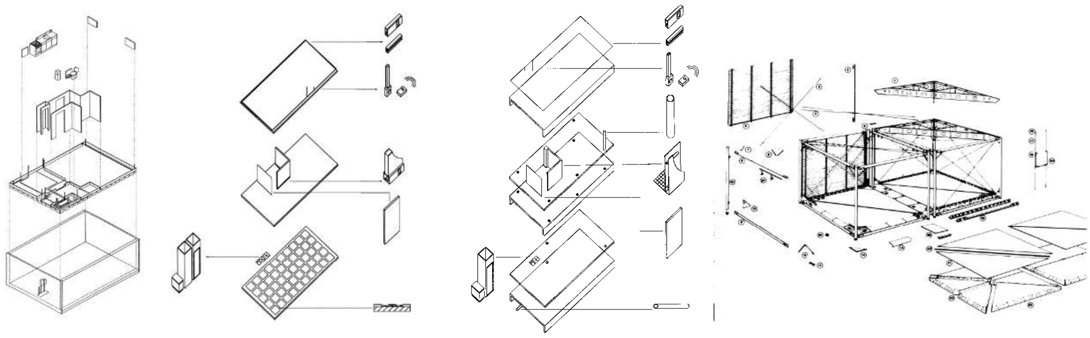

Figure 6: Every type of spatial flexibility results in different hierarchy of building products, Durmisevic 2006

Typical housing in the Netherlands is built using concrete slabs, brick façades, and block-partitioning walls, with installations fixed into the concrete slabs or walls. Although these components have different use and technical life cycles, they are assembled in such a way that they form one fixed physical time level where use and technical life span are set equal. This means that when use life span reaches the end fixed physical level will also reach the end regardless the fact that some elements within one physical level have longer durability.

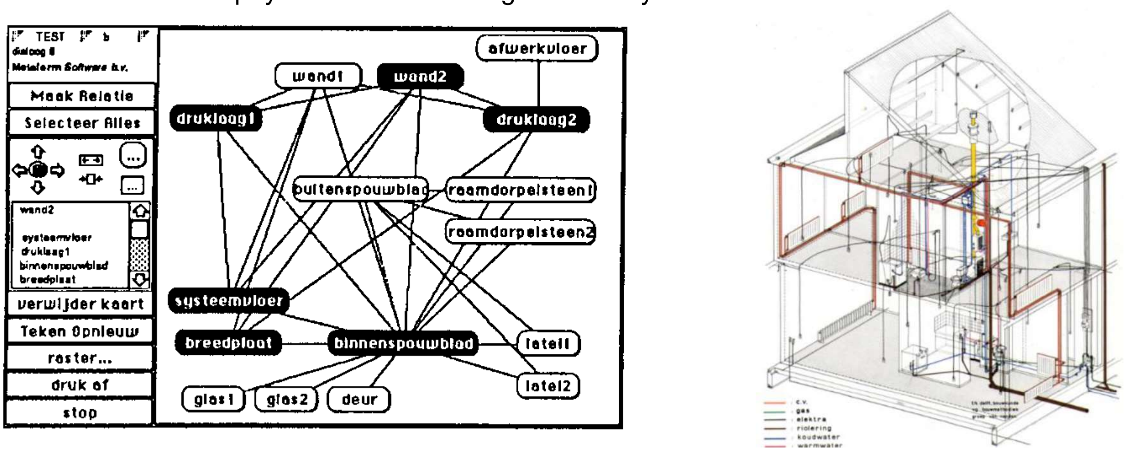

Figure 7: Typical housing projects in the Netherlands in 70's and relational pattern presenting unstructured complex relations between building elements. (Van Randen 1976)

Transformation of such structures is unfeasible as relations between many elements need to be cut in order to extract one element for functional adaptation or upgrade. These dwellings are mostly being demolished. If one would like to increase their use life cycle transformation capacity of the building wold need to be increased by recognising functional layers with different use life cycle as independent physical clusters in the buildings as illustrated in the figure bellow.

The figure illustrates a technical decomposition of a pilot project in Amsterdam using developed flexible infill system (SMR system1999) that took into account independence and exchangeability of user sensitive building levels (indicated by the market research) as partitioning walls, installation walls, bathroom units. Integration of new independent functional and physical levels into an existing building, gave potential to the building do be used longer than anticipated in the first place.

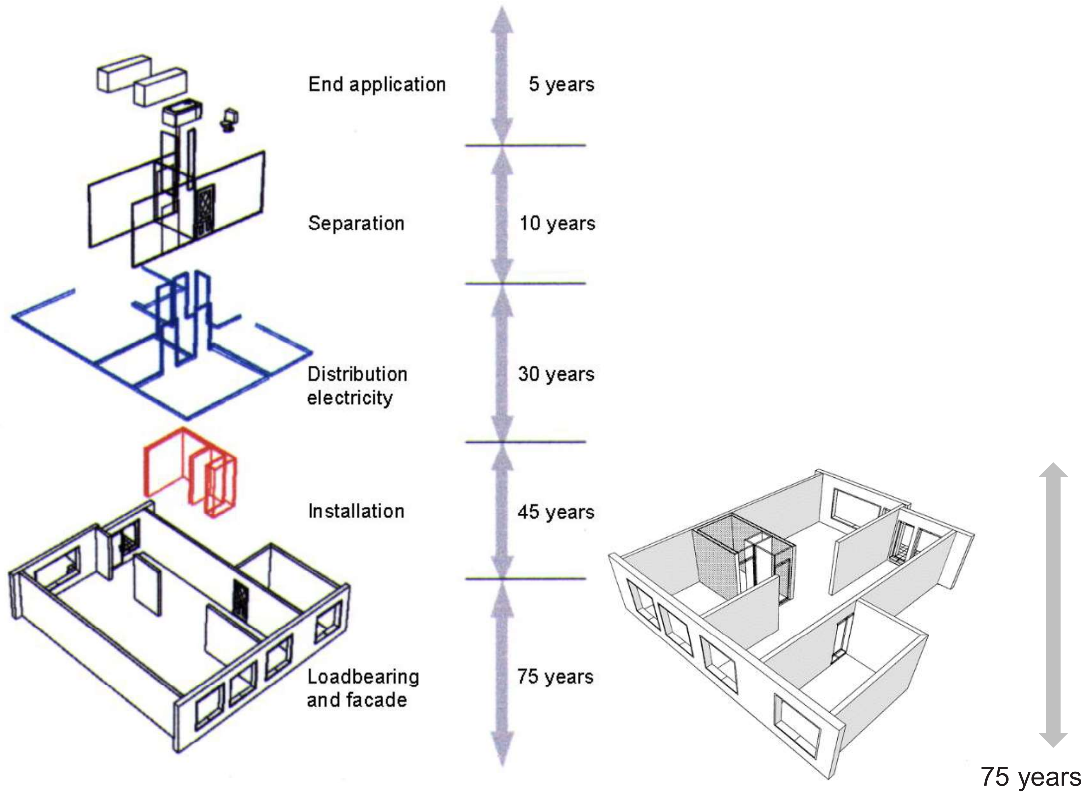

Figure 8 left: Proposal for technical decomposition that increases flexibility of housing in Amsterdam Durmisevic 2006 by addition of five physical levels. Figure right existing housing block as one permanent physical level.

An important contribution of studies by Habraken, Brand, and Duffy is that they indicated already in 70's that building is not a static entity. However, if we want to explore transformation and reuse potential of building elements further than a fixed number of changing levels, as suggested, becomes ambiguous. The number of changing (exchangeable) levels is increasing with the increase of changing user requirements and the need for separation and recovery of building materials. The fact that building materials have different life cycles and that durability of most of materials is longer than durability of their functions forms the bottleneck for transformation. Therefore, the specification and arrangement of materials through technical composition of building, which accounts for the high transformation capacity of building and high reuse potential of materials, is the dominant issue in design of circular reversible buildings.

Towards reversible buildings

When exploring the concept of circular buildings and circularity of material streams through all life cycle phases of the building, aiming to high quality reuse options of buildings and its constitutive parts, three types of reversibility can be identified: Spatial, Structural and Material

They have impact on all building physical levels as building, system, components and material level. Reversibility of these levels are accommodated by transformation actions as; the separation, elimination, addition, relocation, and substitution of parts. (Durmisevic 2006) (Habraken, 1998) and as such determine the level of space transformation, structural transformation and material transformation. (see figure below). By design of reversible structures whose systems and components can be reconfigured, replaced and reused spatial flexibility and adaptability is possible and at the same time material reuse through up/recycling is feasible. Key indicator of such three-dimensional transformation that leads to reversible buildings is disassembly, whereby the dominant agent of such three-dimensional transformable building is capacity of structure to transform. (figure below)

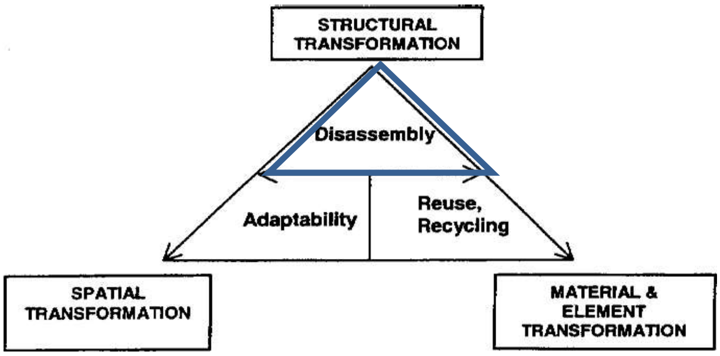

Figure 9: three dimensions of building transformation (Durmisevic 2006)

Ultimately the key indicators of circular buildings is the level of building reversibility which can be measured by transformation capacity of building (on three levels spatial, structural, material) and reuse potential of its parts on three levels (building, system/component, element).

Buildings will last longer if they have capability to transform form one spatial configuration to another and be updated to the new use and technical requirements. This requires certain spatial and structural characteristics that will support spatial and structural reversibility of buildings. Further to this building systems and components will last longer when having capability to be updated/reconfigured to meet new requirements or when its elements can be used to create new products and systems. Considering above mentioned Design of circular buildings runs a danger of being done on ad hock bases without spatial, structural and material aspects of reversibility being integrated into a design protocol from the beginning of a design process.

Building parameters that determine reversibility of building are twofold. They are of spatial and technical nature and deal with interrelated spatial and technical flexibility aspects of buildings. Nevertheless spatial transformation deals with spatial and physical constrains, primarily on building level while structural transformation deals with transformation and reuse potential on system and component level of buildings technical composition. Two models addressing these two key building parameters of reversibility will be discussed further in the paper.

Model addressing transformation potential form spatial point of view

Every building is built with a basic purpose to accommodate human activities and provide shelter. The purpose and need is changing and affecting spatial and technical configuration of built structure. The question is how can we anticipate these changes and take a 4th dimension (the factor time) into design so that buildings can be updated and adopted to new programs, users and their needs instead of being demolished.

The ideal transformation model, that can answer all future scenarios, does not exist. Therefore it is important to understand spatial requirements for transformation scenarios and define set of compatible spatial configurations that will form one transformation model. One transformation model of circular building will be defined by one of reversibility forms of building (see table below). However each building should be design form the outset of one transformation model, thus incorporating different scenarios.

BUILDING LEVEL	scenario 1	scenario 2	scenario 3	scenario 4
Trans-functional	Building for Housing	Office building	Building for Education	Public building
Adaptable mono-functional block	Studio apartment	Urban family apartment	Apartment for elderly	Apartment for disabled
Transportable	location A	Location B	Location C	Location …
1+2+3 transformable	extendable	Trans-functional	Adaptable mono-functional block	transformable

Table 1: Four spatial reversibility forms of transformable building

Each transformation model representing one of above mentioned spatial reversibility forms of building will result into a different hierarchy of physical parts and their composition. This brings us back to the first step in the equation towards reversible building being understanding use scenarios and spatial configurations and the generic technical agents that will facilitate transformations.

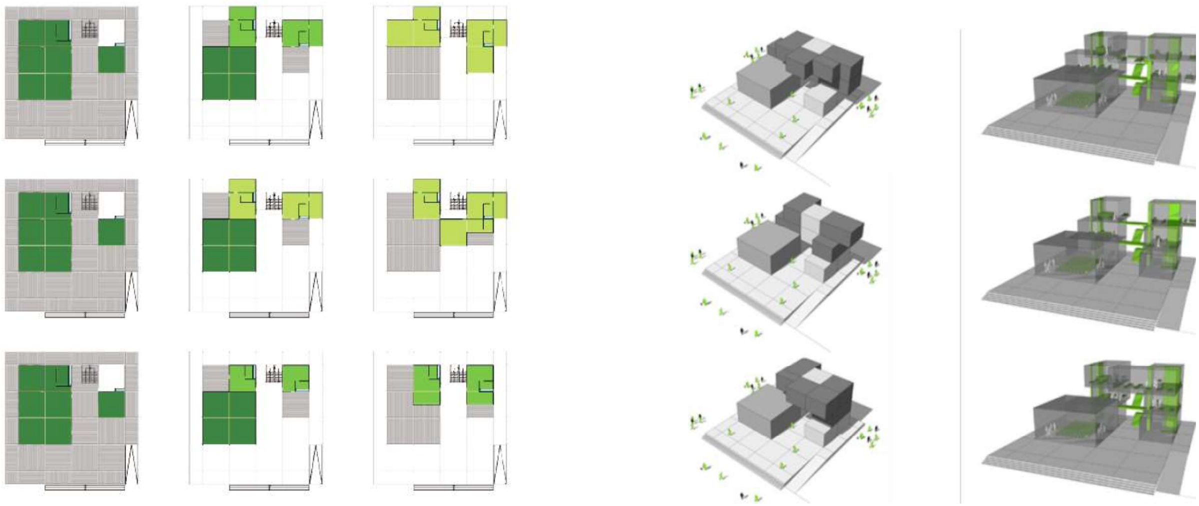

Figure 10: Model representing transformable reversible form of building which incorporates scenario for housing, offices and public spaces. Figure right: Green vertical elements represent agents of transformation.

Besides focus on building capacity to support different spatial configurations (figure left), other parameter that determines spatial adaptability are of technical nature. In other words once scenarios for spatial use have been determined it is necessary to define the agents of transformations that will facilitate transformations of building throughout its use. The better these agents are defined the longer the building will be used. Two main physical agents of transformations are base of the structure which needs to provide for stability of the structure and the carrier of energy and climate concepts. When analyzing these two parameters the main designers question would be what are the minimum number of elements that can provide the maximum number of transformations. (figure right)

Development of a transformation measurement tool for nursing homes in the Netherlands indicated that there are four major parameters that need to be considered for the evaluation of spatial transformation capacity. Those are dimensions dealing with major spatial parameters that determine which use scenario can be accommodated within specific spatial constrains, positions of physical transformation agents (fixed parts of the building), disassembly of mayor systems and capacity of transformation agents.

Figure 11: Parameters determining Transformation potential of buildings on building level addressing capacity to accommodate different spatial configurations (Durmisevic 2009)

Diagram bellow presents four key indicators of transformation potential on building level addressing particularly capacity of building to accommodate different spatial configurations and their impact on technical characteristics. The model maps parameters that address spatial and technical characteristics of building. This model is not addressing structural transformation of building systems and components and their reuse potential as this will be discussed within separate model in next section.

Model addressing structural transformation and reuse potential

Building structures can pass different stages of reversibility. Number and type of reversibility stages will depend on the level of transformation required. Differences can be made from slight functional adjustments where only partial reversibility is taking place to transformation of the structure to a new function whereby the structure needs to be reversed back to the initial set of elements that will be reconfigured into a product with new functionality or existing product with adjusted functionality.

Couple of models that are measuring structural/systems flexibility have been developed in the past.

In 1996, Geraedts proposed the Flexis method, to assess the flexibility of installations and their components (Geraedts, 1996). The method distinguishes four key performance indicators of user flexibility: partitionability, adaptability, extendibility and multi-functionality. Each indicator is composed of a few sub-indicators. For example, the sub-indicators of extendibility are local capacity, central capacity, dimensions of distribution network and location. To get a final score in this method, each of the sub-indicators has to be rated on a 1-5 scale. Geraedts also proposes a set of weighting factors to get a better score.

After 6 years of study Brand concluded successful buildings often have large undefined spaces that are suitable for many purposes (Brand, 1994). A large room size makes it easier for users to adapt the room to their needs. Large undefined spaces are multi-functional. Reports about the IFD program also agree with the need (SenterNovem, 2007), to reconfigure the layout (Crone, 2007).

Durmisevic introduces 'transformation capacity', as a measure of disassembly and reuse potential of a building and its components(Durmisevic 2006). A high transformation capacity means that a building function can be reversed to other function by independent systems, that components are reversible to the set of initial elements, and as a result building can be transformed to fit new functional requirements or its systems and components can be dismantled and reused in new components or buildings. Extensive indicator method is proposed to determine the structural transformation capacity of such building. The method uses a mix of high and low level indicators. The high level indicators assess functional dependencies in the building. The low level indicators assess physical dependence, such as: can components be easily removed?

Indicators of structural transformation capacity and their reversibility deal with functional, technical and physical design domains of structures. As such they determent functional technical and physical dependences/independence within building structures being the precondition for disassembly, transformation and reuse of building systems, components and elements.

The notion of high level and low level indicators suggests that reversibility has to be considered both in concept design and in detailed design phase.

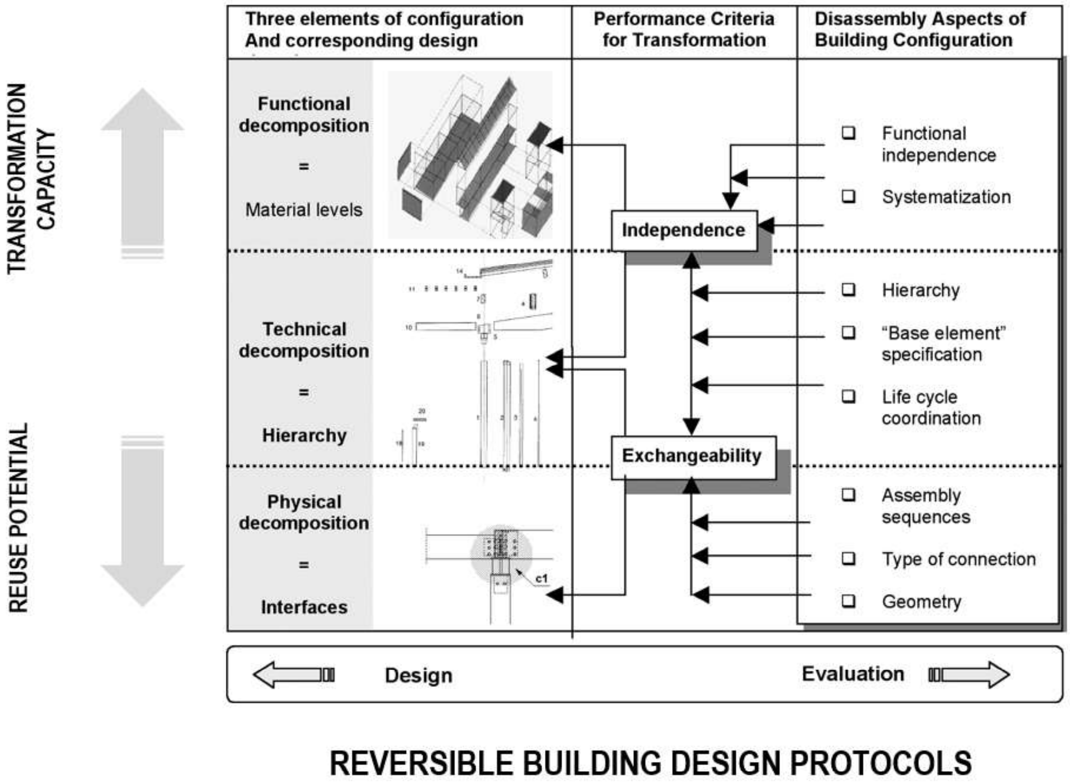

Figure 12 illustrating relation between the deisgn domains of transformable structures, indicators of reversible configurations providing high transformation and reuse potential of buildings and its products, Durmisevic 2006.

As suggested in the models key determents of the successful reversibility of building/component configuration are their ability and ease to accomplish building/component adaptability an material recovery.

An essential part of this approach is to understand how structures work and how they can be reconfigured and modified. Therefore it is useful to understand factors that define typology of reversible configurations.

During configuration design, a designer determines sets of elements and their relations. As a design activity, configuration design can be seen as an activity concerned with different relationships and interdependencies among building materials. The set of relations and materials result in the physical statement of the structure, which informs us how performance requirements are translated into materials, and how materials are integrated into a system or a building.

Configuration in building design means creating an overall solution out of elements. Configuration is closely related to composition. Opposite to this, decomposition, is concerned with splitting up a totality into sub-parts. Composition and decomposition are both related to the ordering of materials, since each configuration is a representation of materials and their relations.

Design of configuration begins with the systematization of materials that provide a certain function. Industrialized building methods offer a possibility to cluster group of parts into modules. Later this group of parts is assembled as a sub-assembly on a building site. Such industrialized way of construction provides better control over the resources used and their reuse options as well as over the number and type of interfaces on the construction site.

The sub-assemblies exist on different levels of technical composition of building. A sub-assembly is a cluster representing building elements that act as one independent building section in production and assembly/disassembly. Elements are seen as the basic parts that form the lowest level of building sub-assembly (components). In the same way that elements can be connected to form low-level sub-assemblies (components), similarly, low-level sub-assemblies can be connected to form high-level assemblies (systems).

Designations such as system, subsystem, component is relative. A subsystem at one level is a component at another level.

According to such a definition of building structure, the hierarchical levels of building/composition decomposition can be defined as:

- The building level represents the arrangement of systems, which are carriers of main building functions (load bearing construction, enclosure, partitioning, and servicing),
- The system level represents the arrangement of components, which are carriers of the system functions (bearing, finishing, insulation, reflection etc) - the sub-functions of the building.
- The component level represents the arrangement of elements and materials, which are carriers of component functions, being sub-functions of the system. (Durmisevic2006)

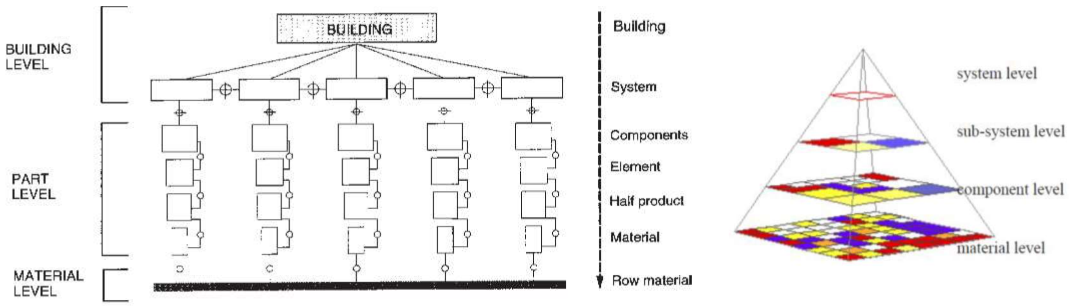

Figure 13: Hierarchy of material levels in building, Durmisevic 2006

Typology of building configuration and its reversibility is defined by three design domains namely functional, technical and physical.

- Functional domain: deals with functional decomposition and allocation of functions into separate materials, which respond differently to changing conditions. This domain defines functional dependences
- Technical decomposition deals with hierarchical arrangement of the materials, and relations as well as with hierarchical dependences between material levels.
- Physical decomposition deals with interfaces that define the physical integrity and dependences of the structure.

These design domains will determine whether two key indicators of structural transformation supported by disassembly potential of building configurations can be met. The two indicators are independence and exchangeability. (Durmisevic2006)

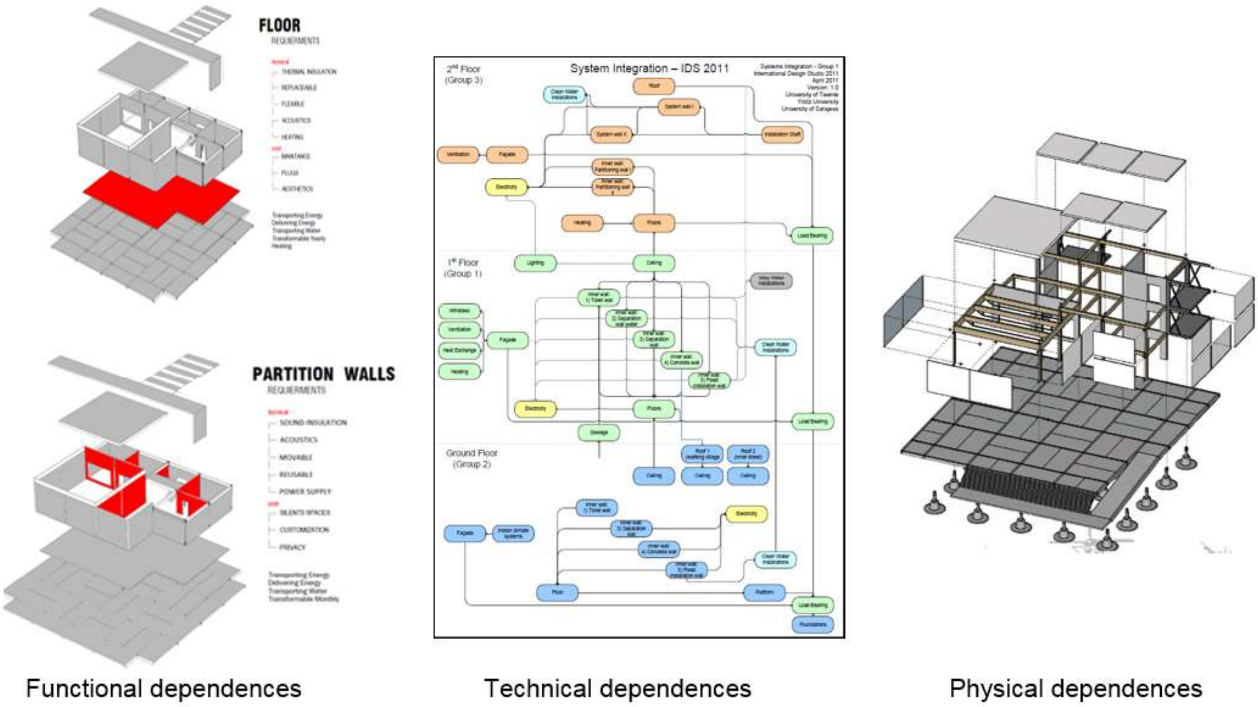

Figure 14: illustration three design domains that deal with three types of dependences within reversible technical configurations (IDS 2011).

- ***Independency***
  "Not requiring or relying on something else" (Merriam-Webster 2013)

  To create a reversible building according to DfD standards independency of components is extremely important. This high level independency is mainly on the functional level and creates an environment in which assembly, transformations functionality without the need for adaptations to other.

- ***Exchangeability***
  "The act or process of substituting one thing for another" (Merriam-Webster 2013)

  As the definition suggests the exchangeability of components refers to the ability to replace one component with another one without damaging component itself and the surrounding components.

Conclusion

Due to climate change, migrations, demographic changes, technological and ICT revolutions, we are witnessing increasing acceleration of change almost on daily bases in all fields. These changes affect the way we communicate, work, travel, live, while trends and predictions risk to be overrun already at the time they are identified as such. What is the physical answer to this increasing dynamics, considering the capacities of the planet and human physical and psychological needs? And if Reversible Buildings, Dynamic Architecture or Green Transformable structure is the answer, how do they look like? (Durmisevic, 2015)

To answer these questions from a building design point of view it is crucial to understand the capabilities of buildings, to transform what is today a negative environmental impact of build environment to a positive one. The complex multi-scale capacities of buildings provide massive potential for a broad range of positive correlation with nature's systems as well as value redefinition of buildings and its components.

This paper addresses two key indicators of building circularity from the Buildings as Material Banks context which introduce new value propositions around buildings and its elements that are based on longer building exploitation due to the buildings capacity to transform special configurations and longer exploitation of building elements and materials based on capacity of structure to be reversed back to reusable elements, to be updated and reconfigured to answer new requirements.

Those are spatial transformation and structural transformation. Bought can be seen as pillars of reversible building. Reversible Building that has capacity to reverse its initial spatial configuration into other spatial organization without waste generation, as well as to reverse structural configuration to initial set of elements to configure new structure. These models will be developed further into an evaluation models that will measure transformation and reuse potential of buildings its components and elements within EU Buildings as Material Banks H2020 project. Further to this based on transformation end reuse potential criteria Reversible building design protocol will be developed that will help designers to design reversible structures form the outset of transformation and associated virtual simulator will inform architects form what the impact of early design decisions are on future transformation and reuse potential integrating environmental and economic factors as well.

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